8-15-2015

A Methodology to Estimate Supply Chain Cost of Low Demand Parts

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A METHODOLOGY TO ESTIMATE SUPPLY CHAIN COST OF LOW DEMAND PARTS

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Thesis submitted to the Faculty of the

Rochester Institute of Technology

In partial fulfillment of the requirements for the degree of

Master of Science in Industrial Engineering

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August 15, 2015

DEPARTMENT OF INDUSTRIAL AND SYSTEMS ENGINEERING

KATE GLEASON COLLEGE OF ENGINEERING

ROCHESTER INSTITUTE OF TECHNOLOGY

ROCHESTER, NEW YORK

CERTIFICATE OF APPROVAL

M.S. DEGREE THESIS

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Acknowledgements

It is a great pleasure to present this report, a written testimony of real fruitful and invaluable research. I take this opportunity to express my feeling of gratitude to the faculty of Industrial & Systems Engineering Department at Rochester Institute of Technology for providing me with an opportunity to work on the research topic of my interest. On completion of this course, I have personally experienced the linkage between theoretical knowledge and its practical implication.

I am deeply indebted and would like to express my gratitude to Dr. Scott Grasman and Dr. Denis Cormier for their guidance and profuse assistance during the research work. Their invaluable support makes this thesis a successful work.

I would like to express my sincere thanks to Dr. Michael Hewitt, Dr. Ruben Proano and Professor John Kaemmerlen who gave me invaluable guidance during this research period.

Last, but not the least, I would like to thank my family for their continuous love and support for my education and my friends, Anirudha, Anshul, Atul, Chaitanya, Mugdha, Nisarth and Vinayak, for making this journey so memorable. I was able to learn and enjoy my learning period as a result of their unconditional backing towards my learning ventures.

Abstract

As according to the Magnuson-Moss Warranty Act, automobile manufacturers are required to provide spare parts for any model they sell, for a minimum span of 10 years. In the automobile/ aviation industry, the demand for replacement parts is generally met using conventional manufacturing processes such as injection molding (IM) and stocking parts in warehouses. IM proves economical when the demand is high and continuous. The demand for replacement parts is generally low and intermittent and stocking parts in inventory to meet future demands proves expensive and the possibility of stock-outs or parts going obsolete is high.

Rapid Manufacturing (RM) is an additive manufacturing technique that prints parts without the need of tools, unlike conventional manufacturing processes. Thus, it saves on the tooling cost, time to make the mold, and the need to stock various parts in order to meet the intermittent demand. There is a need for an alternative approach to meet low volume intermittent demands, and the Just in Time (JIT) production strategy incorporating RM serves as an option. In JIT, production starts when a demand is received from the customer. It also gives the Original Equipment Manufacturer (OEM) an option to make parts on the demand site, eliminating transportation and inventory holding costs.

The objective of this thesis is to develop a decision making framework to determine the economical supply chain strategy to meet the demand for replacement parts. The supply chain strategies considered are in-house manufacturing by the RM process called Selective Laser Sintering (SLS) in a JIT production environment, and stocking parts in centralized warehouses manufactured by IM to meet future demands. A mixed integer programming (MIP) model has been formulated to determine the unit cost of parts for the supply chain strategies under consideration. The results from the model are used to determine the significant part parameters affecting the cost of manufacturing by SLS using Regression Analysis. Based on the results, material volume and height of the part proved to be significant factors and a regression equation has been derived and validated for estimating the unit supply chain cost of parts manufactured by SLS.

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List of Acronyms

FDM: Fused Deposition Modeling

IM: Injection Molding

JIT: Just in time

RM: Rapid Manufacturing

SLS: Selective Laser Sintering

STL: Stereolithography

List of Notations

A: $Thickness\ of\ the\ powder\ layer\ (in)$

B: $Time\ spent\ in\ adding\ a\ layer\ of\ powder\ (sec)$

BBV_P: $Bounding\ box\ volume\ of\ part\ (in^3)$

$C_{ea} = Energy\ consumption\ cost\ to\ add\ powder\ (\$)$

$C_{energy} = Energy\ consumption\ cost\ (\$)$

$C_{es} = Energy\ consumption\ cost\ to\ scan\ parts\ (\$)$

$C_{im} = Cost\ of\ Injection\ Molding\ machine\ (\$)$

$C_{inventory} = Cost\ of\ holding\ inventory\ (\$)$

$C_{labor} = Labor\ cost\ (\$)$

$C_{ma} = Machine\ usage\ cost\ to\ add\ powder\ (\$)$

$C_{machine} = Machine\ usage\ cost\ (\$)$

$C_{material} = Material\ cost\ (\$)$

$C_{mold} = Cost\ of\ mold\ (\$)$

$C_{ms} = Machine\ usage\ cost\ to\ scan\ parts\ (\$)$

$C_{sls} = Cost\ of\ SLS\ machine\ (\$)$

$C_{storage} = Storage\ cost\ (\$)$

$C_{tool} = Tooling\ cost\ (\$)$

$C_{transportation} = Transportation\ cost\ (\$)$

$CE = Cost\ of\ energy\ (\$/kWh)$

$CM = Cost\ of\ material\ (\$/lb)$

$D_m = Density\ of\ material\ (lb/in^3)$

$EC = Energy\ consumption\ (kW)$

$h_{max} = Maximum\ wall\ thickness (in)$

$H: Height\ of\ the\ build\ (in)$

$H_p: Height\ of\ part\ (in)$

$HS: Laser\ scan\ spacing\ in\ the\ Y\ direction\ (in)$

$MT = Available\ Machine\ time$ (sec)

$MU = Percentage\ of\ Machine\ utilization$

$MW = Material\ wastage\ multiplying\ factor$

$N_b = Number\ of\ builds$

$N_i = Number\ of\ parts\ in\ inventory$

$N_m = Number\ of\ parts\ manufactured$

$N_{ps} = Number\ of\ parts\ shipped$

$R_{labor} = Rate\ of labor\ (\$/hr)$

$R_{shipping} = Rate\ of\ shipping\ (\$/lb)$

$R_{storage} = Rate\ of\ storage\ (\$/in^3)$

$RR = Rate\ of\ return\ on\ capital\ invested\ for\ a\ year$

$S_h = Seconds\ in\ an\ hour$

$t_i = Polymer\ injection\ temperature\ (°C)$

$t_m = Mold\ temperature\ (°C)$

$t_x = Part\ ejection\ temperature\ (°C)$

$T_a: Time\ to\ add\ powder\ (sec)$

$T_c: Cooling\ time\ (sec\ )$

$T_{ct}: Molding\ cycle\ time\ (sec)$

$T_d = Time\ to\ change\ die\ (hrs)$

$T_i: Injection\ time\ (sec)$

$T_{Jdelay}: Mirror\ jump\ delay\ (sec)$

$T_{Ldelay}: Mirror\ stabilization\ and\ laser\ switching\ delay\ (sec)$

$T_p: Total\ time\ to\ print\ parts\ (sec)$

$T_{pp} = Pre\ and\ post\ processing\ time\ per\ build\ (hrs)$

$T_s: Time\ to\ scan\ parts\ (sec)$

$V_J: Mirror\ jump\ speed\ (in/sec)$

$V_p = Volume\ of\ part\ (in^3)$

$V_S: Mirror\ scan\ speed\ (in/sec)$

$W_P: Distance\ of\ laser\ travel\ in\ the\ Y\ direction\ of\ cross\ section\ of\ part\ (in)$

$\rho: Ratio\ of\ part\ volume\ to\ bounding\ box\ volume\ of\ part$

$\alpha: Constant$

$\beta = Coefficient\ of\ thermal\ diffusivity$

Chapter 1. INTRODUCTION

1.1 Background on Rapid Manufacturing

Rapid Manufacturing (RM) is a manufacturing process that uses Layer Manufacturing Techniques (LMT) to build 3D products that are part of assemblies or the final product. The material cost, cycle time and capital investment for RM machines is generally high compared to conventional manufacturing processes such as Injection Molding (IM), making it undesirable for manufacturing of products in high or medium volumes. Hopkinson & Dickens (2001) state that the advantages of RM over conventional processes come in the form of zero tool cost, reduced lead time of making the tool, and freedom in product design proves instrumental in accepting the potential benefits to be gained by employing RM.

The prime difference between RM and the traditional machining manufacturing techniques is that RM is not a subtractive manufacturing process, i.e., it does not involve removal of material from the part, thus resulting in minimal material wastage. It is referred to as an Additive manufacturing process. There are many sectors in which the RM technology has been successfully implemented. Chandra et al. (2005) provides an example with people affected by facial deformity, which can be congenital or accidental, needing rehabilitation of the face. RM has been used to create an impression of the patient’s face in addition to the mask which would fit the impression, making it appropriate for the patient to use the mask as per the facial geometry. This is difficult for any conventional manufacturing process.

Rapid Prototyping (RP) and RM techniques provide designers the freedom to change or make modifications in the CAD file at the last moment to facilitate production of parts of any size, any geometry and with reduced time required to make the parts. Wannarumon & Bohez (2004) pointed out the inability of conventional jewelry manufacturing processes such as investment casting to provide these benefits. Berman (2012) studied the application of RM to the footwear industry which allows customization of footwear as per requirements of size, design and color. It eliminates the constraints of conventional manufacturing mechanisms such as the need for cutting of materials and new organization of the work process in manufacturing.

The traditional methodology of creating dental implants is to create a plaster model of an oral impression, then hand carve a wax pattern of how the repaired tooth will look, cast it, and then add a porcelain or ceramic veneer to it. RM substitutes this method by taking a digital scan of the mouth, and then using a CAD program to design the prosthesis. This file is then outputted in STL format, imported into the RM machine which can build the wax mold or if required the tooth itself ("Additive Fabrication Transforms Dental Labs," 2008).

One drawback of some RM processes is the relatively inferior material properties of parts compared to the material properties of those manufactured using traditional processes. In order to get over this drawback and have material properties of parts as good as the ones obtained using traditional manufacturing processes, there has been customized use of materials to suit the need of industries which demand high material properties. This comes at a high cost. Rocketdyne Propulsion and Power has successfully used SLS technology to custom make titanium alloy parts for NASA's space shuttles to withstand high temperature. These parts have already been used successfully in orbit ("The solid future of rapid prototyping," 2001).

RM has been successfully implemented in manufacturing by organizations such as Boeing, NASA, Align Technologies, BMW and Paramount PDS. Boeing's Rocketdyne propulsion and power section have used SLS to manufacture low volumes of parts in space labs and space shuttles ("3D Printing Industry, Explore the Many Uses of FDM | Stratasys," 2014). BMW has adopted RM for manufacturing jigs & fixtures used for assembly and test operations. These jigs and fixtures are built from Acrylonitrile Butadiene Styrene (ABS) using the Fused Deposition Modeling (FDM) process and are much lighter and ergonomically superior compared to the traditionally manufactured jigs and fixtures machined from aluminum and polyamide. BMW also uses RM to create patterns for sand casting ("Direct Digital Manufacturing AT BMW," 2015). Paramount PDS, a product development and RM company in the USA, uses a material which is certified and accredited by independent laboratories complying with regulations to flammability, smoke generation and smoke toxicity. They manufacture flight hardware components for commercial luxury aircraft that enables the aircraft company to cut down on lead times and eliminate tool cost ("Paramount PDS Delivers Flight-Ready Parts for Commercial Aircraft with Rapid Manufacturing with EOS's Flame Retardant Laser-Sintering Material," 2007).

1.2 Problems Faced by OEMs and Options Available With the Use of Rapid Manufacturing

Hasan & Rennie (2008) identified the potential of a RM supply chain in the spare parts industry. The authors addressed the frequently faced problems by the aerospace and automotive industry of unavailability of spare parts. Conventional manufacturing processes such as IM depend on economies of scale for profit, resulting in manufacturing in large quantities to meet future demands. It is difficult to stock all the parts in inventory due to the variety of parts that go into the making of an aircraft or an automobile. Also, many of the parts are not frequently needed, and stocking them proves expensive due to high inventory holding cost. The unavailability of replacement parts keeps the aircrafts grounded, which hurts the airline due to loss of business. The OEM is left with a difficult question to answer as to which parts to stock in inventory and how much to stock.

Pérès & Noyes (2006) addressed the problems faced in the management of spare parts in 'isolated systems'. The supply of parts is made difficult due to the specific environment not being suitable for storing parts due to space constraints. The authors investigated the idea of creating parts on the spot as per demand, and introduced the concept of e-logistics support. They described and classified the various RM techniques and the benefits from using these techniques in remote systems. They also discussed studies based on industrial cases representing different modes of system isolation.

Meadows (1997) addressed the problem faced by the defense department in acquiring spare parts for aircrafts, ships and trucks because many of the systems currently in operation were built decades ago. Platforms such as the B-52 bomber, KC-135 tanker aircraft and the C-130 cargo plane which were built in the mid 90's are expected to remain operational for the foreseeable future. The lack of spare parts to maintain them would result in stoppage in their usage. In addition to these aging systems, even the new F-22 fighter aircraft, the B-2 stealth bomber and the Navy's F/A-18 have been found to face lack of spare parts. The unavailability of parts not only leads to longer logistics cycles for weapons systems but also forces operators to remove parts from operational platforms to replace missing ones in other systems. It is observed that companies with both government and commercial customers have shut down their military lines to pursue higher demands and more profitable opportunities, as the military was not ordering in sufficient quantities to justify keeping production lines open.

The ‘make to stock’ supply chain strategy in which large batches of parts are manufactured, stocked at centrally located warehouses, and supplied on demand has traditionally been used. The positive of employing this strategy is the low lead time of meeting demands. However, the negatives can outnumber the positives of this strategy in some cases. The inventory holding cost is high, the transportation costs from a centralized location are high, and there is always a risk of stock outs or parts going obsolete if there is no demand. Forecasting is the basis of employing this strategy and can result in either overstock or stock out due to varying demand.

The OEM has to shoulder the responsibility for providing speedy service along with minimization of inventory cost. Stocking parts in inventory is a risk as these parts may never be used, and the OEM will have to bear the obsolescence cost. The uncertainty of demand also poses a threat to the suppliers of these OEM’s as they have to bear the cost of raw material produced at their end. The cost of holding inventory is very high as it adds the cost of surplus parts to the capital investment made by the organization. RM technology is an alternative to the conventional manufacturing processes in cases of low demand. The material cost for manufacturing parts by RM is high, but it eliminates the high inventory cost and the risk of stock outs.

The costs associated with the parts vary depending on the process used to manufacture them; the cost of delivering parts depends on the facility location and mode of transportation. If the parts are manufactured by conventional processes such as IM, the costs applicable to these parts are in the form of tool costs, material costs, machining costs, labor costs, inventory costs and transportation costs from central warehouses or distribution centers to the desired location. RM allows freedom in the design of the part as no additional tooling or machining is required in case of a complex geometry which is a drawback of traditional processes.

The use of RM would prove economical and feasible when the demand quantity is low. The inventory cost gets eliminated completely. The transportation cost may apply if the parts are being manufactured at a centralized location, but it gets eliminated if the RM is done at the point of use. There is a need to study the advantages and limitations of the RM technology in the supply chain with respect to the cost and time to meet the demand of parts.

Table 1: Comparison between Rapid Manufacturing and Injection Molding

Manufacturing Process	Advantages	Disadvantages
Rapid Manufacturing	• No tooling cost and lead time to manufacture tool • Ability to manufacture on demand site, eliminating transportation cost • Freedom to make changes in design without additional cost and tooling lead time • Parallel production of different parts • No inventory holding cost	• The printing process is slow • High material cost • Skilled labor required • High machine overhead cost
Injection Molding	• Low cycle time • Low material cost • Low labor cost • Low machine overhead cost	• High tool cost and lead time to manufacture tool • Inventory holding cost is applicable • Transportation cost is applicable • Transportation lead time • Material wastage

1.3 Thesis Objectives

This thesis extends the work on cost analysis of IM and SLS processes by considering energy consumption, and inventory holding and transportation costs. A mathematical model is developed to give the unit supply chain cost of parts manufactured by SLS and IM. Furthermore, a cost equation has been derived for estimating the unit supply chain cost of manufacturing in-house using SLS with part specifications as the input parameters.

The thesis is organized as follows: Chapter 2 is divided in two parts. The first part discusses the various supply chain strategies proposed to meet low intermittent demands. The second part represents literature related to the cost analysis on IM and RM techniques such as Stereolithography (STL), FDM and SLS. Chapter 3 defines the problem statement. Chapter 4 discusses the mathematical model developed to solve the problem including system constraints.

Chapter 5 describes the selection of parameters and their values as input to the mathematical model. Chapter 6 presents numerical experiments performed using the mathematical model, deriving the equation to predict the unit supply chain cost of parts manufactured in-house using SLS and validating the results. Finally, Chapter 7 discusses the conclusions and future work.

Chapter 2. LITERATURE REVIEW

The first section of the literature review presents a study on various supply chain theories and strategies. The second section presents work related to the cost analysis of plastic parts manufactured using IM and RM processes such as STL, FDM and SLS.

2.1 Supply Chain Theories and Strategies

There has been extensive research in the field of Supply Chain Management addressing problems faced in manufacturing. This literature review focuses on the Supply Chain theories and strategies addressing uncertain demand and replacement parts incorporating RM.

2.1.1 Supply chain strategies to meet uncertain demands

Fisher (1997) introduced the concept of matching supply chain strategies to the right level of demand uncertainty of a product in case of high obsolescence and/or stock out cost. The author summarized that the critical decisions to be made are not always about minimizing production and distribution costs but about positioning inventory and available production capacity in order to meet uncertain demand. Similarly, the suppliers should be chosen not only for their low cost but for their flexibility and speed as well. Holmström, Louhiluoto, Vasara, & Hoover (2001) suggested that in order to minimize delivery times and to fulfill orders, a wide range of products have to be stocked in inventory resulting in large inventory costs. The authors discussed that suppliers can offer value to customers and improve their operations without weighing the benefits of customer service against cost by changing the demand supply chain.

Christopher (2000) mentioned that short product life cycle, global economic and competitive forces create uncertainty, turning the market turbulent and volatile. The author suggested that ‘agility’ is the key to surviving in this scenario by creating responsive supply chains. The author made a distinction between the philosophies of ‘lean’ and ‘agility’ and pointed out that the challenge to supply chain management in such a volatile market is to develop lean strategies up to the decoupling point and agile strategies beyond that.

Christopher & Towill (2001) suggested that in some markets, meeting customer expectation by getting the right product at the right price and at the right time is critical for competitive success.

The authors mentioned that the lean philosophy is powerful when the winning criterion is cost but when customer service is the winning criteria, agility is the way to go. The authors explored the combination of lean and agility as a hybrid strategy to create a cost effective and responsive supply chain. The authors proposed three ways in which the lean and agile philosophies could co-exist; the Pareto approach, the de-coupling point approach and the separation of base and surge demands.

2.1.2 Supply chain strategies for replacement parts incorporating rapid manufacturing

Huiskonen (2001a) addressed the requirements for planning the logistics of spare parts differently from other materials due to sporadic demand, difficulty in forecasting, and high part prices. The author studied the effects of various operational control characteristics such as criticality, specificity, demand pattern and value of spare parts on the logistics system design (service strategy, supply structure, supply chain relationship and inventory control system).

The impact of the use of RM on the supply chain management of replacement parts in the aircraft and automotive industry has been of interest to many supply chain specialists such as Walter, Holmstrom, & Yrjola (2004) and Holmstrom (2010). Walter et al. (2004) and Holmstrom (2010) addressed supply chains in which both manufacturing and distribution are challenging. The spare parts supply in the aircraft industry served a perfect example for their study because of the rapid repairs and maintenance required to avoid losses due to aircraft being grounded. They studied the problems faced by aircraft OEM's in dealing with the demand for replacement parts. Their study found out that the major concern of the OEM is the wide range of parts that an aircraft is made up of and the impracticality of storing all parts in inventory due to the high inventory holding cost and uncertain demand. They also pointed out the issue of parts going obsolete if stocked to cover the entire life cycle, given the long life cycle of these parts in addition to the declining service lives of aircrafts. They also highlighted the high cost and time required for manufacturing parts on demand using conventional manufacturing processes such as IM. They analyzed the drawback of having both frequently and infrequently required parts stored in inventory and delivered as per the demand from centralized warehouses of the OEM to the demand site.

The various proposed supply chain strategies to deal with the problem of service parts is tabulated below:

Table 2: Supply Chain strategies for service parts

Author	**Strategy**
Jan Holmstrom, 2010 Christopher & Towill, 2001	Centralized RM machine for slow moving type B and C parts
Jan Holmstrom, 2010	Centralized warehousing and centralized RM machine
Wohlers & Grimm, 2002	Centralized multiple RM machines
Pérès & Noyes, 2006	Demand site RM machine

Ruffo, Tuck, & Hague (2007) carried out an analysis to decide if an OEM should invest directly in an RM machine for employing the distributed RM supply chain strategy or outsource infrequently needed replacement parts to suppliers having expertise in the RM technology. The authors summarized the pros and cons of make or buy decisions followed by the effect of RM technology on the outsourcing decision. The authors focused on two strategies for their analysis, both showing the cost effectiveness of in-house manufacturing over outsourcing.

- In-house manufacturing or outsourcing using traditional manufacturing resources.
- In-house manufacturing using RM if resources and skills are available or outsource to RM suppliers.

Huiskonen (2001b) categorized spare parts on the basis of their criticality (high or low) and specificity (standard or customized). They suggested that categorization along these lines is more efficient in managing the supply chain of spare parts compared to the classification of these parts on the basis of profitability (ABC) as per the Pareto rule. The author however did not validate his analysis with data.

2.2 Cost Analysis of Parts

A cost analysis was performed by Hopkinson & Dickens (2001) in which they compared the manufacturing cost per part required to produce four different parts varying in size, by IM and SLS. The cost parameters considered for the analysis were fixed machine costs, and variables costs including machine operation cost, material cost and tooling cost. The material from which the parts were to be manufactured was selected to be polypropylene. The results showed that the unit cost of the parts manufactured by SLS was constant irrespective of the number of parts manufactured. The authors inferred that small parts with high geometric complexity made in low volumes were best suited for manufacturing using SLS technology.

Another cost analysis was performed by Hopkinson & Dicknes (2003) to compare the unit cost of parts manufactured in a time frame of one year using IM and the three RM processes SLA, FDM, and SLS. The analysis was carried out on two plastic components differing in size. The cost parameters considered for the analysis were machine cost, material cost, labor cost and tooling cost. It was observed that the total number of parts manufactured in a year by each process differed as a result of different production speeds, with FDM being the slowest followed by SLA, and then SLS. The contribution of the machine cost, material cost and labor cost to the total cost were different for the three RM processes. The contribution of machine cost to the total cost of part manufactured by SLA and FDM was highest followed by material cost. On the contrary, the material cost was the highest contributor to the total cost of part manufactured by SLS, because the unsintered material is not reused. The machine cost for SLS was lower compared to SLA and FDM as the machine was capable of building a higher number of parts due to a high build rate. It was observed that the cost per part was highest for SLA followed by FDM and SLS. Figure 1 shows that for the small part, the production quantity at which IM is cheaper was greater for SLS compared to the SLA and FDM processes. Figure 2 shows that for the large part, the production quantity at which IM is cheaper was greater for FDM compared to SLA.

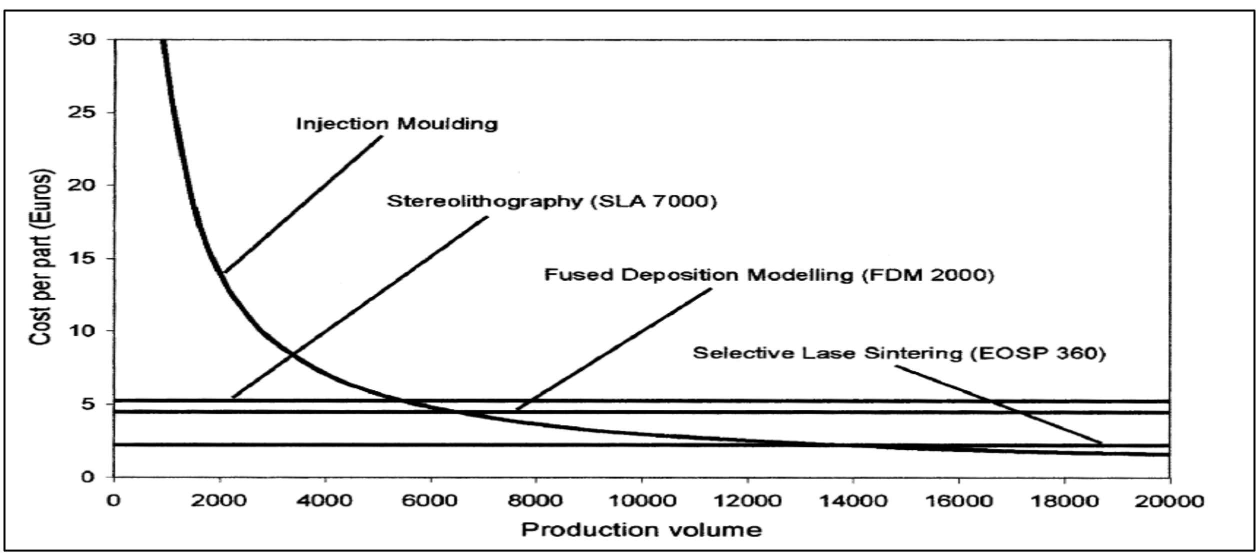


Figure 1: Cost comparison for small part (Hopkinson & Dickens, 2003)

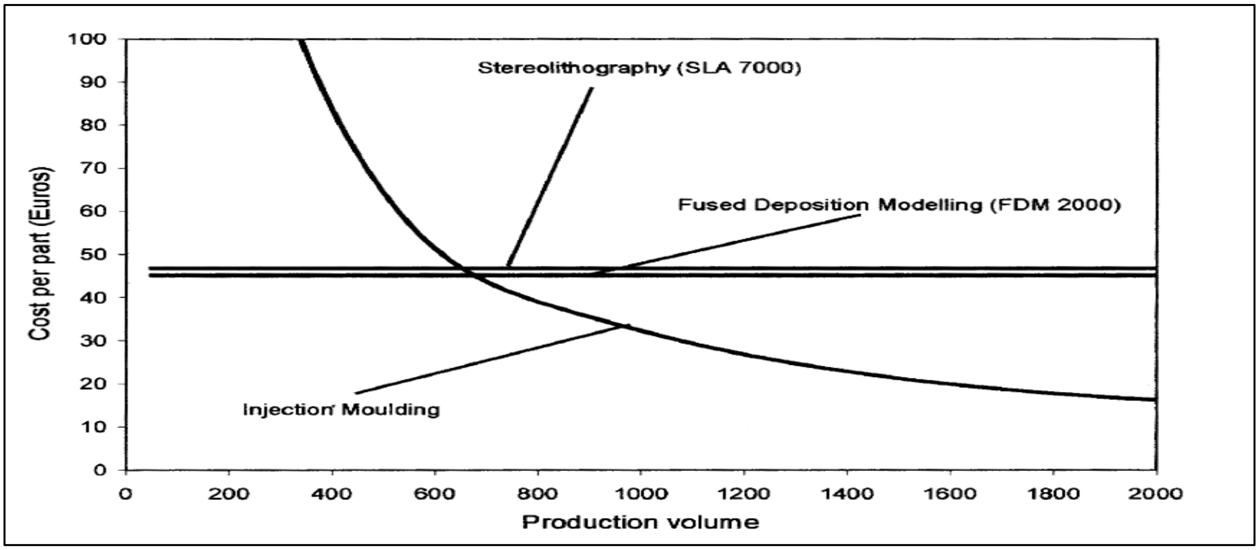


Figure 2: Cost comparison for large part (Hopkinson & Dicknes, 2003)

The above graphs infer that the cost per part is constant irrespective of the production quantity for SLA, FDM and SLS respectively; whereas the cost per part decreases in case of IM as the tool cost gets amortized by the production quantity. The comparisons proved that IM is a cheaper process for high production volumes. It was observed that apart from low production volumes, the production rate and material cost made it difficult to opt for RM for large parts. When the manufacture of parts with complex geometries was analyzed, injection molded parts required additional machining to meet the part geometry, adding to the final cost of parts. Thus, small parts having complex geometries and small production volumes were deemed to be best suited for RM process. The above analysis is a good approximation when the RM machines are manufacturing copies of the same part and the production volume is high.

Another cost model was developed by Ruffo, Tuck, & Hague (2006) in which the authors considered the impact of investments and overheads on the per part cost. The authors categorized costs as direct and indirect in which material cost was considered to be direct and machine absorption, labor and maintenance costs were considered to be indirect costs. They assigned indirect costs to the parts on a machine working time basis. The authors assumed the machine utilization to be 57% compared to 90% assumed by Hopkinson & Dicknes (2003). Their results showed a saw tooth shaped curve which had deflections for low production volumes unlike the constant cost from Hopkinson & Dicknes (2003). The cost curve had a tendency to change whenever a row in the x-direction was used, a new layer was required, or when a new bed was required due to the filling of machine bed space as shown in Figure 3. Part size and the packing ratio were drivers of the cost model and influenced the initial transition and the stabilized value of the curve. The authors inferred that large parts occupy a large portion of the machine bed resulting in the cost being split between fewer parts. The packing ratio, which is affected by part size, influences both build time and material waste.

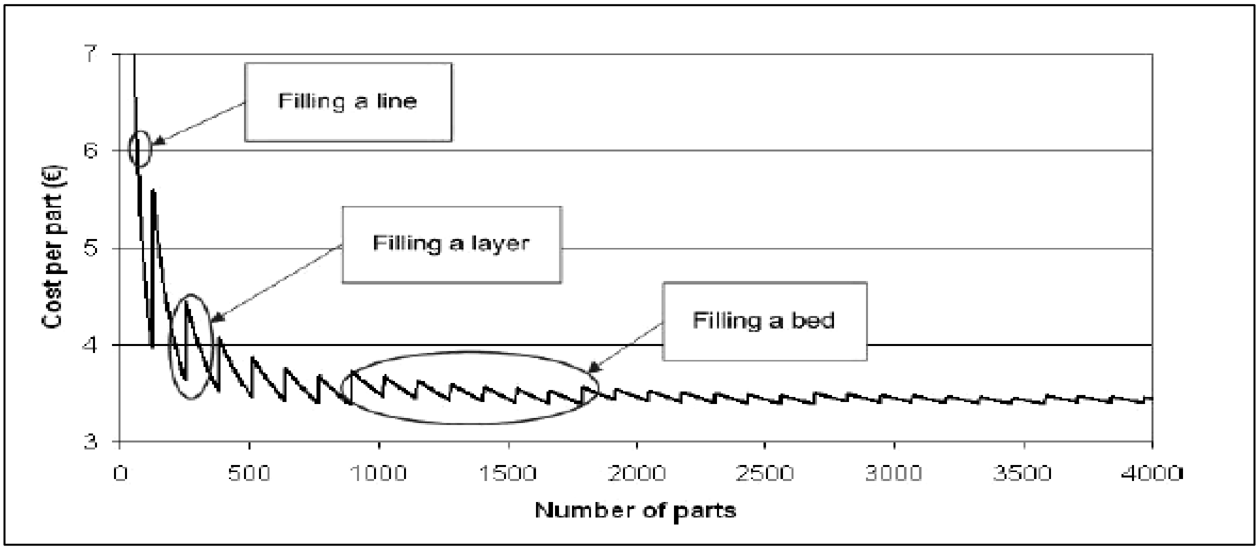


Figure 3: Production curve for the lever (M. Ruffo et al., 2006)

A method for cost calculation of mixed parts in the same build envelops, referred to as 'Parallel Production', was developed by Ruffo & Hague (2007). They proposed three different mathematical models for the cost estimation of the SLS process and compared them through a case study. Their proposed approaches were as follows:

- Cost of a single part was first calculated as a fraction of the total cost using the ratio between volume of the part and the total volume of production. In their previous research, Ruffo et al. (2006) demonstrated that the part volume, considered singularly, is not enough for time and cost estimation. Thus, they proposed a different solution.
- An alternate solution proposed calculating cost of a single part by splitting the full build cost into different parts placed on the machine bed. The error with this approach was the poor packing ratio used for calculation due to the machine bed being partially empty.
- Finally, they proposed calculating cost of a single part based on the cost of a part built in a high volume production.

The authors tested the third methodology in two scenarios, one in which the machine builds copies of the same part, and the other in which the machine employs parallel production of mixed components. Figure 4 displays their results which suggest that when different components are efficiently mixed in the building space, the cost of each component decreases.

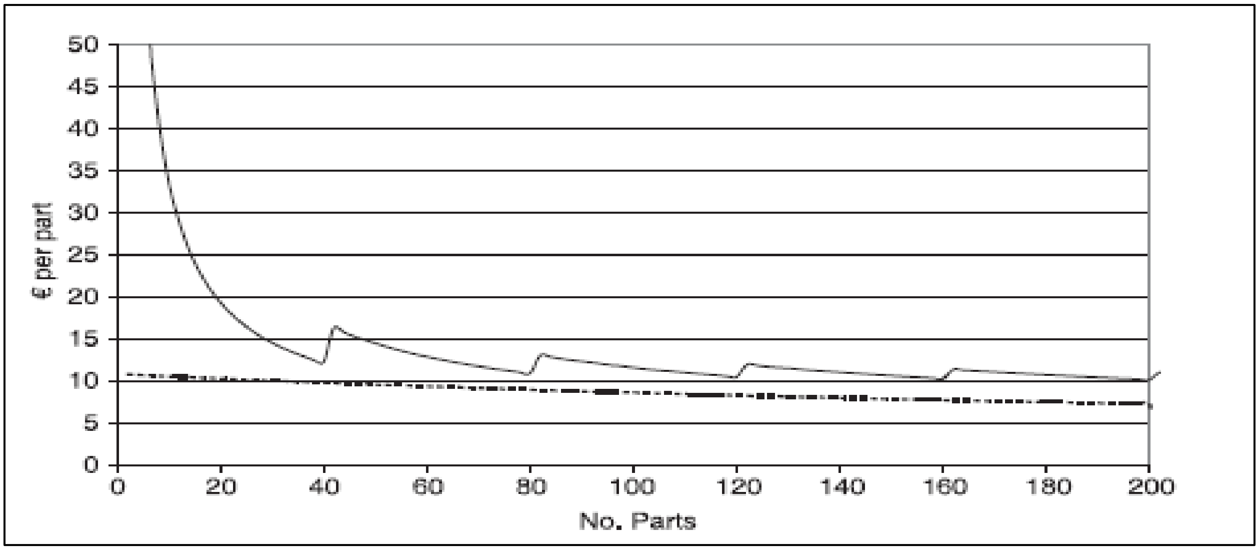


Figure 4: Comparison between production curves for the spring clip in single part and mixed production scenarios (M. Ruffo & Hague, 2007)

A study on the interrelation between redesign and cost estimation was carried out by Atzeni, Iuliano, Minetola, & Salmi (2010). The authors pointed out that a remarkable cost reduction is obtained when the component shape is modified to exploit the advantages of RM. The authors considered material cost and processing costs (part design and testing cost, machine cost, labor cost, post-processing cost) for RM and mold, assembly, machine, material and labor costs for IM. They didn't consider administrative overhead, energy, space rental or ancillary equipment costs. The authors compared the cost per part for IM against production volumes ranging 5,000 to 500,000 parts. They compared the per part cost for two different SLS machines; the P390 which has a smaller bed volume compared to the P730 machine. A sensitivity analysis was carried out varying each cost parameter for both IM and SLS. It was observed that the mold cost was the sole significant contributor to the unit cost of part manufactured by IM, whereas machine and material cost was the significant contributor to the unit cost of parts manufactured by SLS. Figure 5 summarizes the contribution of mold cost, assembly cost, machine cost, material cost and labor cost per part for different production volumes. Figure 6 summarizes the contribution of machine, material, labor and assembly cost per part manufactured using the two SLS machines under consideration.

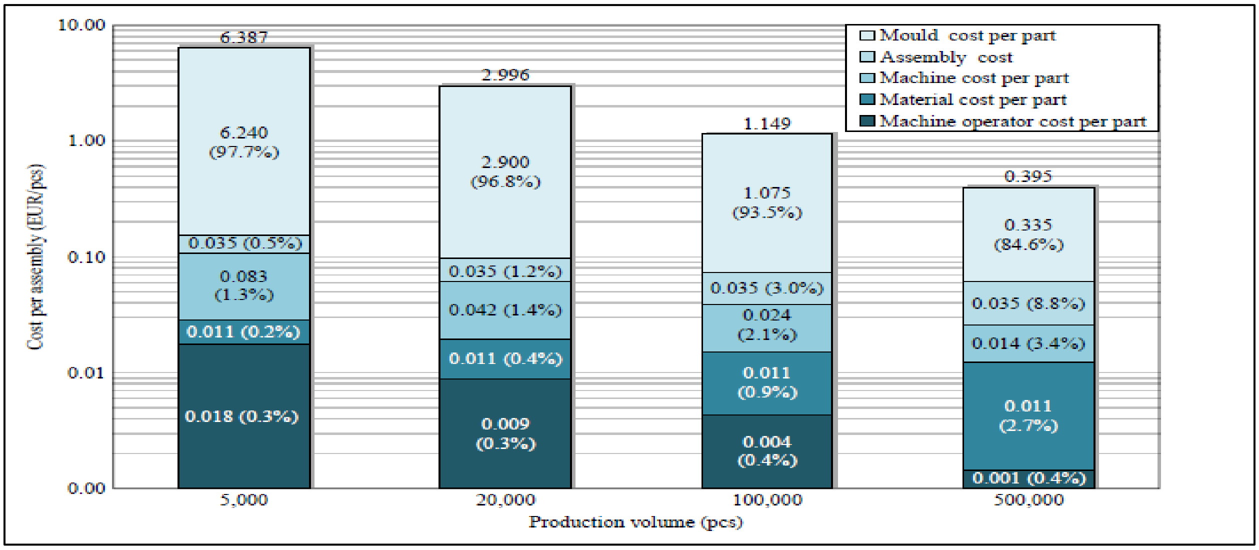


Figure 5: Total cost of the lamp holder manufactured by IM for different production volumes (Atzeni et al., 2010)

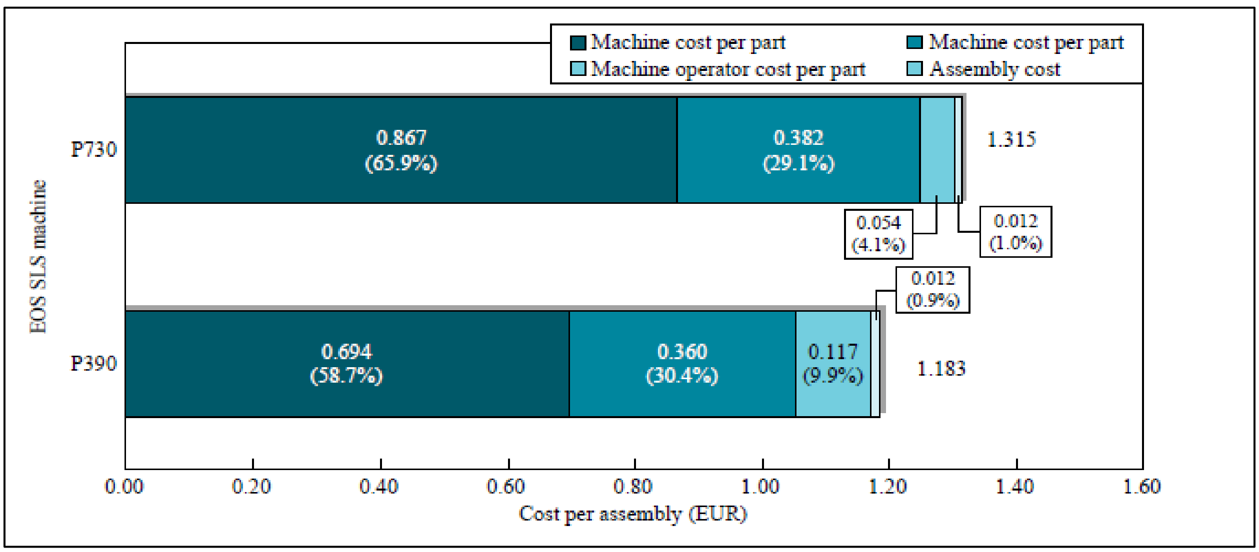


Figure 6: Total cost of the lamp holder manufactured by SLS for the two EOS machines (Atzeni et al., 2010)

The studies carried out by Hopkinson & Dickens (2001) and Hopkinson & Dickens (2003) have focused on determining the crossover point in which one switches from RM to IM in terms of unit cost with respect to production volume for the parts under consideration. The research carried out by Ruffo, Tuck & Hague (2006) focused on determining part size and the packing ratio as the factors affecting the unit cost of part. Ruffo & Hague (2007) extended their research in determining the effect of parallel production on the unit cost of parts. A quantitative analysis on the supply chain cost of parts considering the two manufacturing processes RM and IM hasn't been done. Also, the part specifications affecting the unit cost of part manufactured by RM hasn't been looked into.

Chapter 3. PROBLEM DEFINITION

Consider an organization ABC that receives demand for a variety of parts in different quantities. At present, ABC has been fulfilling its customer's demand by delivering parts stocked in their central warehouse that were manufactured by IM. ABC has been in situations where either the stocked parts have gone obsolete resulting in obsolescence cost, or they ran short on parts. The organization is looking for an alternate approach and is planning to adopt the JIT production strategy incorporating SLS wherein they could start production only after a demand is received from the customer. This production strategy would help them reduce the risk of bearing the obsolescence cost and stock outs.

The objective of ABC is to minimize the supply chain cost of meeting demand. ABC is aware of the advantages using SLS, but is also skeptical of the unit cost of manufacturing parts by SLS when the packing ratio is low. ABC is therefore planning to perform an analysis before investing on the SLS machine upfront. The questions they want to address are as follows:

- Which part specifications affect the cost of manufacturing in-house using SLS significantly?
- Which supply chain strategy is cheaper for given part specifications?

With the above scenario in mind, this thesis develops a cost estimation model to determine the supply chain cost of parts considering machine, energy consumption, material, labor and transportations costs for parts produced using RM with the SLS process. For comparison, the machine, energy consumption, tooling, material, labor, storage, inventory holding and transportation costs for IM are calculated. The two manufacturing approaches are compared using the following supply chain strategies:

- In-house manufacturing using SLS
- Stocking parts in warehouses manufactured by IM

A statistical analysis is performed to determine the significant factors affecting the unit cost of parts manufactured by SLS, and a regression equation is derived and validated to determine the unit cost of part manufactured by SLS.

Chapter 4. MATHEMATICAL FORMULATION

The parameters affecting the per part cost are considered to be direct and indirect costs. The machine usage, energy consumption and labor costs are considered to be indirect costs while the material and transportation costs are considered to be direct costs for both the SLS and IM processes. Tooling cost is applicable only for the IM process and is considered to be an indirect cost. The storage cost and inventory holding costs are applicable for parts manufactured by IM, and transportation cost is applicable if the outsourcing strategy is opted for meeting the demand of parts. The machine usage and energy consumption costs are considered to be functions of the machine working time for both the SLS and IM processes.

Pham & Wang (2000) presented an approximate method to predict the build times for the SLS process. The authors divided the time to manufacture parts using SLS as the time to spread powder, idle time before sintering, and the time to scan parts. The time to spread powder depends on the height of the build, and the time to scan parts depend on the volume of parts on the machine bed to be scanned. The idle time is negligible and can be ignored. The authors considered factors like the roller travel speed, build height, laser scan speed, scan area and the part volume to determine the time function. The time function is as follows:

$$T_p = T_a + T_s \tag{1}$$

where,

$$T_a = \left[B * \frac{H}{A}\right] \tag{2}$$

$$T_s = \left[\frac{[BBV_P * \rho * e^{\alpha * (1-\rho)}]}{[HS * A]} * \frac{1}{[V_J - [\rho * e^{\alpha * (1-\rho)}] * [V_J - V_S]]}\right] + \left[\frac{[W_p * H_p]}{[HS * A]}\left[4 * T_{Ldelay} + T_{Jdelay}\right]\right] \tag{3}$$

Similarly, for IM the machine usage and energy consumption costs are function of the injection time and the molding cycle time. According to product costing guidelines compiled by Sebastian & Shaun (2010) the molding cycle time is calculated as the sum of injection time (T_i) and cooling time (T_c):

$$T_{ct} = T_i + T_c \tag{4}$$

where,

$$T_c = \left[\frac{h_{max}^2}{\pi^2 * \beta}\right] * \left[\log_e \frac{[4(t_i - t_m)]}{[\pi(t_x - t_m)]}\right] \tag{5}$$

The injection time is usually between 1 – 2 seconds. It should be noted that the values obtained from the above equations are in seconds. Appropriate conversions are made according to requirements in the cost functions and constraints in the following sections.

4.1 Cost Functions for SLS

The costs contributing to the per part cost for the SLS manufacturing process are as follows:

- Machine usage cost
- Energy consumption cost
- Material cost
- Labor cost

4.1.1 Machine usage cost

The machine usage cost is a function of the machine working time. It is calculated as the sum of cost to add powder and cost to scan parts. The cost to add powder is calculated as a ratio of the total time taken to add powder and the available machine time in the planning horizon multiplied by the cost of machine. The cost to scan parts is calculated as a ratio of the total time taken to scan parts and the available machine time in the planning horizon multiplied by the cost of the machine. The machine working time to add powder (T_a) and scan parts (T_s) are taken from equations (2) and (3).

$$C_{ma} = \left[\frac{T_a}{MT * MU}\right] * C_{sls} \tag{6}$$

$$C_{ms} = \left[\frac{T_s * N_m}{MT * MU}\right] * C_{sls} \tag{7}$$

4.1.2 Energy consumption cost

The energy consumption cost is also a function of the machine working time. The energy consumption cost is calculated as the sum of cost to add powder and the cost to scan parts. The cost to add powder is calculated as the product of time taken to add powder, power requirement and cost of energy. The cost to scan parts is calculated as the product of the total time taken to scan parts, power requirement, and cost of energy. The time taken to add powder (T_a) and scan parts (T_s) are taken from equations (2) and (3).

$$C_{ea} = \left[\frac{T_a}{S_h}\right] * PR * CE \tag{8}$$

$$C_{es} = \left[\frac{T_s * N_m}{S_h}\right] * PR * CE \tag{9}$$

4.1.3 Material cost

The material cost is a function of the mass of part to be scanned. It is calculated as the product of the number of parts manufactured, the volume of the parts, the density of the material, and the cost of material.

$$C_{material} = N_m * V_p * D_m * CM \tag{10}$$

4.1.4 Labor cost

The labor cost is a function of the number of builds required to manufacture parts. It is calculated as the product of the number of builds required, the pre and post processing time required per build, and the hourly labor wage.

$$C_{labor} = N_b * T_{pp} * R_{labor} \tag{11}$$

4.2 Cost Functions for IM

For IM, the costs contributing to the per part cost are as follows:

- Machine usage cost
- Energy consumption cost
- Tooling cost
- Material cost
- Labor cost
- Storage cost
- Inventory holding cost
- Transportation cost

4.2.1 Machine usage cost

The machine usage cost is a function of the molding cycle time. It is calculated as a ratio of the total molding cycle time required to manufacture parts and the available machine time in the planning horizon multiplied by cost of machine. The molding cycle time is taken from equations (4) and (5).

$$C_{machine} = \left[\frac{T_{ct} * N_m}{MT * MU}\right] * C_{im} \tag{12}$$

4.2.2 Energy consumption cost

The energy consumption cost is also a function of the molding cycle time. It is calculated as the sum of cost to run machine and the cost of injection molding parts. The cost to run machine is calculated as the product of total molding cycle time required to manufacture parts, power requirement and cost of energy. The cost of injection molding parts is calculated as the product of energy consumption of each molding cycle, number of parts produced and the cost of energy. The molding cycle time is taken from equations (4) and (5).

$$C_{energy} = \left[\frac{T_{ct} * N_m}{S_h}\right] * PR * CE + [EC * N_m * CE] \tag{13}$$

4.2.3 Tooling cost

It is assumed for the cost analysis part of this research that the tool is available and the tooling cost is calculated as the expected return on the tool cost for the planning period.

$$C_{tool} = C_{mold} * RR \tag{14}$$

4.2.4 Material cost

The material cost is a function of the volume of part to be manufactured. It is calculated as the product of the number of parts manufactured, the volume of the parts, the density of material, and the cost of material. An additional 3% cost is considered as material wastage cost. The material cost is calculated as follows:

$$C_{material} = N_m * V_p * D_m * CM * MW \tag{15}$$

4.2.5 Labor cost

The labor cost is calculated as the hourly labor wage multiplied by the sum of time taken to change molds and the time taken to manufacture parts.

$$C_{labor} = \left[T_d + \frac{[T_{ct} * N_m]}{S_h}\right] * R_{labor} \tag{16}$$

4.2.6 Storage cost

The storage cost is calculated as the product of number of parts stored, volume of parts and the rate of storage.

$$C_{storage} = N_i * V_p * R_{storage} \tag{17}$$

4.2.7 Inventory holding cost

The inventory holding cost is calculated by adding the machine usage, energy consumption, material, labor and storage costs for the number of parts stocked in inventory. This cost is multiplied by the opportunity cost for holding inventory in each time period.

$$C_{inventory} = \left[C_{machine} + C_{energy} + C_{material} + C_{labor} + C_{storage}\right] * N_i * RR \tag{18}$$

4.2.8 Transportation cost

The transportation cost is a function of the weight of the part to be shipped and the speed of delivery. It is calculated as the product of number of parts shipped, volume of part, density of material and the rate of transportation by mode of delivery selected.

$$C_{transportation} = N_{ps} * V_p * D_m * R_{shipping} \tag{19}$$

A mixed integer linear programming mathematical model has been developed to determine the cost of parts considering the system constraints. Consider an OEM who needs to determine which supply chain strategy needs to be adopted to meet the demand of part *p*, $p \in \{1...P\}$. The OEM has the option to manufacture by SLS on demand site *dn*, $dn \in \{1..DN\}$ in time period *t*, $t \in \{1..T\}$ or ship parts stocked at a centrally located warehouse *cl*, $cl \in \{1...CL\}$ manufactured by IM. The OEM has the option to ship parts using the mode of shipment *mps*, $mps \in \{1...MPS\}$. The notations, objective function and constraints in the model are explained below:

Sets

$p \in \{1..P\}$ $Set\ of\ parts$

$cl \in \{1..CL\}$ $Set\ of\ centralized\ locations$

$dn \in \{1..DN\}$ $Set\ of\ demand\ nodes$

$mps \in \{1..MPS\}$ $Set\ of\ modes\ of\ package\ shipment$

$l \in \{1..LAYERS\}$ $Set\ of\ layers$

$t \in \{1..T\}$ $Set\ of\ time\ periods$

Parameters

<u>*Machine cost parameters*</u>

C_{sls}: $Cost\ of\ SLS\ Machine$ (\$)

C_{im}: $Cost\ of\ IM\ Machine$ (\$)

<u>*Variable cost parameters*</u>

PR: $Power\ requirement$ (kW)

CE: $Cost\ of\ energy$ $(\$/kWh)$

R_{labor}: $Rate\ of\ labor\ wage$ $(\$/hour)$

$R_{storage}$: $Rate\ of\ storage$ $(\$/cu.in)$

RR: $Rate\ of\ return\ on\ investment$ (%)

CD: $Cost\ of\ Duraform\ PA$ $(\$/lb)$

CN: $Cost\ of\ nylon$ $(\$/lb)$

RS_{mps}: $Rate\ of\ shipping\ by\ mode$ (mps) $(\$/lb)$

<u>*SLS process parameters*</u>

B: $Powder\ spreading\ time\ including\ the\ time\ delay\ between\ two\ consecutive\ delays$ (sec)

T_{pp}: $Pre\ and\ post\ processing\ time/build$ $(hours)$

Vr: $Roller\ travel\ speed$ (in/sec)

Hm: $Height\ of\ machine\ bed$ (in)

A: $Thickness\ of\ powder\ layer$ (in)

HS: $Laser\ scan\ speed\ in\ the\ Y\ direction\ of\ the\ part$ (in)

Vj: $Mirror\ jump\ speed\ (in/sec)$

Vs: $Mirror\ scanning\ speed\ of\ machine\ (in/sec)$

$Tldelay$: $Mirror\ stabilization\ and\ laser\ switching\ delay\ (sec)$

$Tjdelay$: $Mirror\ jump\ delay\ (sec)$

α: $Empirical\ Constant$

DD: $Density\ of\ Duraform\ PA\ (lb/in^3)$

IM process parameters

MC_p: $Mold\ cost\ of\ part\ (p)$

T_d: $Time\ to\ change\ die\ (hours)$

DN: $Density\ of\ nylon\ (lb/in^3)$

h_{max}: $Maximum\ wall\ thickness\ of\ part\ (in)$

TD: $Thermal\ diffusivity\ of\ material\ (in^2/sec)$

T_i: $Injection\ time\ (sec)$

TM_p: $Time\ to\ make\ mold\ of\ part\ (p)\ (days)$

MW: $Material\ wastage\ multiplying\ factor$ (%)

Part parameters

V_p: $Volume\ of\ part\ (in^3)$

L_p: $Length\ of\ part\ (in)$

W_p: $Width\ of\ part\ (in)$

H_p: $Height\ of\ part\ (in)$

BBV_p: $Bounding\ box\ volume\ of\ part\ (in^3)$

CS_p: $Cross\ section\ of\ part\ (in^2)$

BBH_p: $Bounding\ box\ height\ of\ part\ (in)$

BV_m: $Build\ volume\ of\ machine\ build\ (in^3)$

CS_m: $Cross\ section\ of\ machine\ bed\ (in^2)$

Other parameters

PH: $Number\ of\ years\ in\ the\ planning\ horizon$ (years)

d: $Lead\ time\ (days)$

$MT: Available\ machine\ time\ in\ the\ planning\ horizon\ (sec)$

$MU: Machine\ uptime\ (\%)$

$S_h: Number\ of\ seconds\ in\ an\ hour$

$H_d: Number\ of\ hours\ in\ a\ day$

$Demand_{p,dn,t}: Demand\ of\ part\ (p)\ at\ demand\ node\ (dn)\ in\ time\ period\ (t)$

$T_{mps}: Time\ of\ delivery\ by\ mode\ (mps)\ (days)$

$Inv_{p,cl}: Inventory\ of\ part\ (p) manufactured\ by\ IM\ at\ central\ location\ (cl)$

Variables

<u>Binary decision variables</u>

$Y_{cl}: 1\ if\ IM\ facility\ at\ central\ location\ (cl)\ exists$

$Z_{dn}: 1\ if\ SLS\ facility\ at\ demand\ node\ (dn)\ exists$

$Mold_{p,cl}: 1\ if\ IM\ is\ used\ to\ manufacture\ part\ (p) at\ cental\ location\ (cl)$

$M_{p,cl,t}: 1\ if\ IM\ is\ used\ to\ manufacture\ part\ (p) at\ cental\ location (cl) in\ time\ period\ (t)$

$B_{p,l,dn,t}: 1\ if\ part\ (p)\ is\ manufactured\ in\ layer\ (l)\ at\ demand\ node (dn)\ in\ time\ period\ (t)$

$Tr1_{cl,dn,mps,t}: 1\ if\ supply\ of\ parts\ manufactured\ by\ IM$

<u>Integer variables</u>

$Man1_{p,l,dn,t}: Number\ of\ part (p)\ manufactured\ in\ layer (l)\ by\ SLS\ in\ time\ period\ (t)\ at\ demand\ node\ (dn)$

$NB_{dn,t}: Number\ of\ builds\ in\ time\ period\ (t)\ by\ SLS\ at\ demand\ node\ (dn)$

$Man2_{p,cl,t}: Number\ of\ parts\ (p)\ manufactured\ in\ time\ period\ (t)\ by\ IM\ at\ central\ location\ (cl)$

$IIM_{p,cl,t}: Inventory\ of\ part\ (p) in\ time\ period\ (t)\ manufactured\ by\ IM\ at\ central\ location\ (cl)$

$T1_{p,cl,dn,mps,t}: Number\ of\ parts\ supplied, manufactured\ by\ IM$

<u>Continuous variables</u>

$H_{l,dn,t}: Height\ of\ layer\ (l)\ manufactured\ by\ SLS\ in\ time\ period\ (t)\ at\ demand\ node (dn)$

$CMSLS_p: Material\ cost\ of\ part (p)\ manufactured\ by\ SLS$

$C_{mp}: Machine\ utilization\ cost\ for\ adding\ layers\ by\ SLS$

$CMS_p: Machine\ utilization\ cost\ of\ part (p)\ for\ sintering\ parts\ by\ SLS$

$C_{ea}: Cost\ of\ energy\ consumption\ in\ adding\ layers\ by\ SLS$

$CES_p: Cost\ of\ energy\ consumption\ in\ sintering\ part\ (p)\ by\ SLS$

$CL_{sls}: Labor\ cost\ of\ parts\ manufactured\ by\ SLS$

$TCSLS_p: Total\ cost\ of\ manufacturing\ part\ (p)\ by\ SLS$

$TAL_{dn,t}: Time\ to\ add\ layers\ in\ time\ period\ (t) at\ demand\ node\ (dn)$

$TSP_{dn,t}: Time\ to\ sinter\ parts\ in\ time\ period\ (t) at\ demand\ node\ (dn)$

$TTSLS_{dn,t}: Total\ time\ to\ manufacture\ parts\ by\ SLS\ in\ time\ period\ (t)\ at\ demand\ node\ (dn)$

$CMIM_p: Material\ cost\ of\ part(p)\ manufactured\ by\ IM$

$CMUIM_p: Machine\ utilization\ cost\ of\ part(p)\ manufactured\ by\ IM$

$CMUIM1_p: Machine\ utilization\ cost\ of\ part(p)\ stocked\ in\ inventory\ manufactured\ by\ IM$
$at\ the\ beginning\ of\ time\ period\ 1$

$CMUIM2_p: Machine\ utilization\ cost\ of\ part(p)\ stocked\ in\ inventory\ manufactured\ by\ IM$

$CEIM_p: Energy\ consumption\ cost\ of\ part\ (p)\ manufactured\ by\ IM$

$CLIM_p: Labor\ cost\ of\ part(p)\ manufactured\ by\ IM$

$CIIM_p: Inventory\ holding\ cost\ of\ part(p)\ manufactured\ by\ IM$

$CIIM1_p: Inventory\ holding\ cost\ of\ part(p)\ manufactured\ by\ IM\ at\ the\ beginning\ of\ time\ period\ 1$

$CSIM_p: Storage\ cost\ of\ part(p)\ manufactured\ by\ IM$

$CTIM_p: Transportation\ cost\ of\ part(p)\ manufactured\ by\ IM$

$TCIM_p: Total\ cost\ of\ part(p)\ manufactured\ by\ IM$

$TIM_{p,cl,t}: Time\ to\ manufacture\ part\ (p)\ by\ IM\ at\ central\ location\ (cl) in\ time\ period\ (t)$

Objective function

<u>*Minimize cost:*</u> (20)

$$\sum_{cl\epsilon CL} Y_{cl} + \sum_{dn\epsilon DN} Z_{dn} + \sum_{p\epsilon P} TCIM_p + \sum_{cl\epsilon CL} \sum_{dn\epsilon DN} \sum_{mps\epsilon MPS} \sum_{t\epsilon T} Tr1_{cl,dn,mps,t} +$$
$$\sum_{p\epsilon P} \sum_{l\epsilon LAYERS} \sum_{dn\epsilon DN} \sum_{t\epsilon T} B_{p,l,dn,t} + \sum_p TCSLS_p$$

***Constraints*:**

To model the selection of the source of the manufacturing facility and the transportation links between the facilities and the demand nodes, the binary variables are introduced for the design decisions.

Manufacturing linking constraint

The first type of relationship is between the manufacturing process and the location of the manufacturing facility. Part (p) is manufactured at either the central location or the demand location only if they exist. Equations (21) and (22) show the relationship discussed above in the form of inequalities.

$$\sum_{p \epsilon P} \sum_{l \epsilon LAYERS} \sum_{t \epsilon T} Man1_{p,l,dn,t} \le \boldsymbol{M} * Z_{dn} \quad \forall\, dn \,\epsilon\, DN \tag{21}$$

$$\sum_{p \epsilon P} \sum_{t \epsilon T} Man2_{p,cl,t} \le \boldsymbol{M} * Y_{cl} \qquad \forall\, cl \,\epsilon\, CL \tag{22}$$

SLS machine constraints

The SLS machine builds parts in layers. The number of parts that can fit into each layer depends on the cross section of the machine bed. The number of layers that can be accommodated in a build depends on the sum of the heights of the layers. In case of mix production, the height of a layer is determined by the height of the largest part in that layer. The above description is transformed into inequalities in equations (23 - 26).

The following linking constraint determines if part (p) is manufactured on layer (l).

$$Man1_{p,l,dn,t} \le \boldsymbol{M} * B_{p,l,dn,t} \qquad \forall\, p \,\epsilon\, P, l \,\epsilon\, LAYERS, dn \,\epsilon\, DN, t \,\epsilon\, T \tag{23}$$

The following constraint limits the number of parts in a particular layer of the machine bed.

$$\sum_{p \epsilon P} Man1_{p,l,dn,t} * CS_p \le CS_m \qquad \forall\, l \,\epsilon\, LAYERS, dn \,\epsilon\, DN, t \,\epsilon\, T \tag{24}$$

The following constraint calculates the height of each layer.

$$H_{l,dn,t} \ge B_{p,l,dn,t} * BBH_p \qquad \forall\, p \,\epsilon\, P, l \,\epsilon\, LAYERS, dn \,\epsilon\, DN, t \,\epsilon\, T \tag{25}$$

The following constraint calculates the number of builds required to manufacture parts.

$$NB_{dn,t} \ge \frac{\sum_{l \epsilon LAYERS} [H_{l,dn,t}]}{H_m} \qquad \forall\, p \,\epsilon\, P, l \,\epsilon\, LAYERS, dn \,\epsilon\, DN, t \,\epsilon\, T \tag{26}$$

Production capacity constraint

The build time functions from equations (1), (2) and (3) are used to model the capacity constraint for the SLS machine. The production capacity of the SLS machine at the demand node in each time period is transformed into inequalities in equations (27 - 33).

$$TTSLS_{dn,t} \leq MT * UT \qquad \forall\, dn \in DN, t \in T \qquad (27)$$

where,

$$TTSLS_{dn,t} = TAL_{dn,t} + TSP_{dn,t} \qquad (28)$$

$$TAL_{dn,t} = \left\lceil \frac{\sum_{l \in LAYERS} \left\lceil B * \frac{H_{l,dn,t}}{A} \right\rceil}{S_h} \right\rceil \qquad \forall\, dn \in DN, \forall\, t \in T \qquad (29)$$

$$TSP_{dn,t} = \left\lceil \frac{\sum_{p \in P} \sum_{l \in LAYERS} \left\lceil \left[(\Phi_p * \Psi_p) + \Upsilon_p \right] * Man1_{p,l,dn,t} \right\rceil}{S_h} \right\rceil \qquad \forall\, dn \in DN, \forall\, t \in T \qquad (30)$$

$$\Phi_p = \frac{BBV_p * \left[\left(\frac{V_p}{BBV_p} \right) * e^{\left[\alpha * \left(1 - \frac{V_p}{BBV_p} \right) \right]} \right]}{HS * A} \qquad (31)$$

$$\Psi_p = \frac{1}{Vj - \left[\left[\left(\frac{V_p}{BBV_p} \right) * e^{\left[\alpha * \left(1 - \frac{V_p}{BBV_p} \right) \right]} \right] * (Vj - Vs) \right]} \qquad (32)$$

$$\Upsilon_p = \left[\left(\frac{W_p * H_p}{HS * A} \right) * \ (4 * Tldelay + Tjdelay) \right] \qquad (33)$$

The molding cycle time function from equations (4) and (5) are used to model the capacity constraint for the IM machine. The production capacity of the IM in each time period is transformed into inequalities in equations (34) and (35).

$$TIM_{p,cl,t} \leq MT * UT \qquad \forall\, p \in P, cl \in CL, t \in T \qquad (34)$$

where,

$$TIM_{p,cl,t} = \left[\frac{\left[\left[\frac{\left[\vartheta * h_{max}{}^2 \right]}{\beta} + T_i \right] * Man2_{p,cl,t} \right]}{S_h} \right] \qquad \forall\, p \in P, cl \in CL, t \in T \qquad (35)$$

$$\vartheta = \frac{1}{\pi} \left[log_e \frac{[4(t_i - t_m)]}{[\pi(t_x - t_m)]} \right] \qquad (36)$$

Mold making cost and mold changing time linking constraints

The cost of making a mold is applicable if part (p) is manufactured by IM. Equation (37) shows this relationship in the form of an inequality.

$$\sum_{t \epsilon T} Man2_{p,cl,t} \le \boldsymbol{M} * Mold_{p,cl} \qquad \forall\, p \in P, cl \in CL \qquad (37)$$

$$Inv_{p,cl} \le \boldsymbol{M} * Mold_{p,cl} \qquad \forall\, p \in P, cl \in CL \qquad (38)$$

The time to change molds is to be considered every time a part is manufactured by IM at a central location (cl) in time period (t). Equation (39) shows this relationship in the form of an inequality.

$$Man2_{p,cl,t} \le \boldsymbol{M} * M_{p,cl,t} \qquad \forall\, p \in P, cl \in CL, t \in T \qquad (39)$$

Inventory constraints

Equations (40) and (41) calculate the inventory in time period (t) for each part (p) manufactured by IM.

Inventory of parts at the central location at the beginning of time period 1.

$$Inv_{p,cl} + Man2_{p,cl,t} - \sum_{dn \epsilon DN} \sum_{mps \epsilon MPS} T1_{p,cl,dn,mps,t} = IIM_{p,cl,t} \qquad \forall\, p \in P, cl \in CL, t \in 1 \qquad (40)$$

Inventory of parts at the central location after time period 1.

$$IIM_{p,cl,t-1} + Man2_{p,cl,t} - \sum_{dn \epsilon DN} \sum_{mps \epsilon MPS} T1_{p,cl,dn,mps,t} = IIM_{p,cl,t} \ \forall\, p \in P, cl \in CL, t \epsilon 2..T \ (41)$$

Lead time constraints

The total time to manufacture parts by SLS is the summation of the pre and post processing time per build, time to add powder and time to scan parts. The total time should be within the desired lead time at the demand node. Equation (42) expresses this relationship in the form of an inequality.

$$\frac{[NB_{dn,t} * T_{pp}] + TTSLS_{dn,t}}{H_d} \leq d \qquad \forall\, dn \in DN, t \in T \qquad (42)$$

The time to make the mold set up the mold, and manufacture and transport parts from the central location to the demand node should be within the desired lead time. Equation (43) expresses this relationship in the form of an inequality.

$$[Mold_{p,cl} * TM_p] + \frac{[M_{p,cl,t} * T_d] + \sum_{t \in T} TIM_{p,cl,t}}{H_d} + \sum_{t \epsilon T} [Tr1_{cl,dn,mps,t} * T_{mps}] \leq d$$

$$\forall\, p \in P, cl \in CL, dn \in DN, mps \in MPS \qquad (43)$$

Transportation constraints

The cost and time of shipping parts from the central facility to demand node has to be considered if demand is met from parts stocked at a central location. Equation (44) expresses this relationship in the form of inequalities.

The binary variable takes the value 1 if transportation of parts takes place from central location (cl) to demand node (dn).

$$T1_{p,cl,dn,mps,t} \leq \boldsymbol{M} * Tr1_{cl,dn,mps,t} \qquad \forall\, p \in P, cl \in CL, dn \in DN, mps \in MPS, t \in T \ (44)$$

Cost variables

Equation (45) calculates the machine utilization cost of parts stocked in inventory at the central location at the beginning of time period 1.

$$CMUIM1_p = \left[\frac{\sum_{cl \in CL}\left[\frac{[\vartheta * h_{max}{}^2]}{\beta} + T_i\right] * Inv_{p,cl}}{MT * UT}\right] * C_{im} \ \forall\, p \in P, t \in T \qquad (45)$$

Equation (46) calculates the inventory holding cost of parts at the beginning of time period 1. It is the summation of energy consumption, labor, material, storage and machine utilization costs to manufacture parts in inventory multiplied by the rate of holding inventory.

$$CIIM1_p = \left[\left[\frac{\sum_{cl \in CL}\left[\left[\frac{\vartheta * {h_{max}}^2}{\beta}\right] + T_i\right] * Inv_{p,cl}}{S_h}\right] * [PR * CE * RR + R_{labor} * RR] + \sum_{cl \in CL} Inv_{p,cl} * EC * CE * RR + \sum_{cl \in CL}\left[MW * DN * CN * V_p * Inv_{p,cl} * RR\right] + \sum_{cl \in CL}\left[V_p * Inv_{p,cl} * R_{storage} * RR\right] + \left[CMUIM1_p * RR\right]\right] \quad \forall\, p \in P$$

(46)

Equation (47) calculates the machine utilization cost of parts stocked in inventory from time period 2 onwards.

$$CMUIM2_p = \left[\frac{\sum_{cl \in CL}\sum_{t \in T}\left[\left[\frac{\vartheta * {h_{max}}^2}{\beta}\right] + T_i\right] * IIM_{p,cl}}{MT * UT}\right] * C_{im} \qquad \forall\, p \in P \qquad (47)$$

Equation (48) calculates the material cost of parts manufactured by IM.

$$CMIM_p = \sum_{cl \in CL}\sum_{t \in T}\left[MW * DN * CN * V_p * Man2_{p,cl,t}\right] \qquad \forall\, p \in P \qquad (48)$$

Equation (49) calculates the machine utilization cost of parts manufactured by IM in all time periods.

$$CMUIM_p = \left[\frac{\sum_{cl\, \epsilon\, CL} \sum_{t\, \epsilon\, T} \left[\left[\frac{\vartheta * {h_{max}}^2}{\beta}\right] + T_i\right] * Man2_{p,cl,t}}{MT * UT}\right] * \ C_{im} \qquad \forall\, p\, \epsilon\, P \qquad (49)$$

Equation (50) calculates the energy consumption cost of parts manufactured by IM in all time periods.

$$CEIM_p = \left[\frac{\sum_{cl\, \epsilon\, CL} \sum_{t\, \epsilon\, T} \left[\left[\frac{\vartheta * {h_{max}}^2}{\beta}\right] + T_i\right] * Man2_{p,cl,t}}{MT}\right] * PR * CE \ + \sum_{cl\, \epsilon\, CL} \sum_{t\, \epsilon\, T} Man2_{p,cl,t} * EC * \ CE$$

$$\forall\, p\, \epsilon\, P \qquad (50)$$

Equation (51) calculates the labor cost of parts manufactured by IM in all time periods.

$$CLIM_p = \left[\frac{\sum_{cl\, \epsilon\, CL} \sum_{t\, \epsilon\, T} \left[\left[\frac{\vartheta * {h_{max}}^2}{\beta}\right] + T_i\right] * Man2_{p,cl,t}}{MT}\right] * R_{labor} \ + \ \sum_{cl\, \epsilon\, CL} \sum_{t\, \epsilon\, T} \left[M_{p,cl,t} * T_d * R_{labor}\right]$$

$$\forall\, p\, \epsilon\, P \qquad (51)$$

Equation (52) calculates the cost of storing parts in inventory for all time periods as follows:

$$CSIM_p = \ \sum_{cl\, \epsilon\, CL} \sum_{t\, \epsilon\, T} \left[IIM_{p,cl,t} * V_p * R_{storage}\right] \qquad \forall\, p\, \epsilon\, P \qquad (52)$$

Equation (53) calculates the inventory holding cost of parts stocked in inventory as the summation of energy consumption, labor, material, storage and machine utilization costs multiplied by the rate of return on investment.

$$CIIM_p =$$

$$\left[\left[\frac{\sum_{cl\, \epsilon\, CL} \sum_{t\, \epsilon\, T} \left[\left[\frac{\vartheta * {h_{max}}^2}{\beta}\right] + T_i\right] * IIM_{p,cl,t}}{MT}\right] * [PR * CE * RR + R_{labor} * RR] + \sum_{cl\, \epsilon\, CL} \sum_{t\, \epsilon\, T} \left[IIM_{p,cl,t} * \right.\right.$$

$$EC * CE * RR] + \sum_{cl \in CL} \sum_{t \in T} \left[MW * DN * CN * V_p * IIM_{p,cl,t} * RR\right] + \left[CSIM_p * RR\right] + \left[CMUIM2_p * RR\right]\Bigg] \qquad \forall\, p \in P \qquad (53)$$

Equation (54) calculates the transportation cost of parts shipped from the central location to demand node manufactured by IM.

$$CTIM_p = \sum_{cl \in CL} \sum_{t \in T} \sum_{mps \in MPS} \sum_{t \in T} \left[T1_{p,cl,dn,mps,t} * RS_{mps} * V_p * DN12\right] \qquad \forall\, p \in P \ (54)$$

Equation (55) calculates the tooling cost as the product of mold cost and the rate of return on the investment per year.

$$CM_p = \left[Mold_{p,cl} * MC_p * RR * PH\right] \qquad \forall\, p \in P \ (55)$$

Equation (56) calculates the total cost of parts manufactured by IM and transported to demand site.

$$TCIM_p = \left[CMIM_p + CMUIM_p + CEIM_p + CLIM_p + CIIM1_p + CIIM_p + CSIM_p + CTIM_p + CM_p\right] \qquad \forall\, p \in P \ (56)$$

Equation (57) calculates the SLS machine cost at the demand node to add powder.

$$C_{mp} = \left[\frac{\sum_{l \epsilon LAYERS} \sum_{dn \epsilon DN} \sum_{t \epsilon T} \left[B * \frac{H_{l,dn,t}}{A}\right]}{MT * UT}\right] * C_{sls} \qquad (57)$$

Equation (58) calculates the SLS machine cost at demand node to scan parts.

$$CMS_p = \left[\frac{\sum_{l \epsilon LAYERS} \sum_{dn \epsilon DN} \sum_{t \epsilon T} \left[\left[(\Phi_p * \Psi_p) + Y_p\right] * Man1_{p,l,dn,t}\right]}{MT * UT}\right] * C_{sls} \qquad \forall\, p \in P \quad (58)$$

Equation (59) calculates the energy consumption cost to add powder.

$$C_{ea} = \left[\frac{\sum_{l \epsilon LAYERS} \sum_{dn \epsilon DN} \sum_{t \epsilon T} \left[B * \frac{H_{l,dn,t}}{A}\right]}{S_h}\right] * PR * CE \qquad (59)$$

Equation (60) calculates the energy consumption cost to scan parts.

$$CES_p = \left[\frac{\sum_{l\epsilon LAYERS}\sum_{dn\epsilon DN}\sum_{t\epsilon T}\left[\left[(\Phi_p * \Psi_p) + \Upsilon_p\right] * Man1_{p,l,dn,t}\right]}{S_h}\right] * PR * CE \qquad \forall\, p\, \epsilon\, P \quad (60)$$

Equation (61) calculates the material cost to manufacture parts using SLS at the demand location.

$$CMSLS_p = \sum_{l\epsilon LAYERS}\sum_{dn\epsilon DN}\sum_{t\epsilon T}\left[Man1_{p,l,dn,t} * DD * CD * V_p\right] \qquad \forall\, p\, \epsilon\, P \qquad (61)$$

Equation (62) calculates the labor cost to manufacture parts using SLS at demand location.

$$CL_{sls} = \sum_{dn\epsilon DN}\sum_{t\epsilon T}\left[NB_{dn,t} * R_{labor} * T_{pp}\right] \qquad (62)$$

Equation (63) calculates the total cost of manufacturing parts using SLS at demand location.

$$TCSLS_p = \left[C_{mp} + CMS_p + C_{ea} + CES_p + CMSLS_p + CL_{sls}\right] \qquad \forall\, p\, \epsilon\, P \qquad (63)$$

Chapter 5. RESEARCH METHODOLOGY

A set of parameters values were to be selected as input data to the mathematical model presented in Chapter 4. These parameters are listed below:

1. Type of part
2. Process capability and machine specifications (SLS and IM)
3. Demand quantity
4. Cost and time parameters

The selection of values for the above mentioned parameters is elaborated in the following sub sections.

5.1 Type of Part

The complexity and size of part to be manufactured is an important factor which influences the unit cost of parts manufactured by IM. The IM process is typically used to manufacture thin walled cylindrical, cubical and complex geometries, while the SLS process can manufacture thicker cylindrical, cubical and complex geometries too. SLS can be used to manufacture parts of any complexity without the need of additional processing to achieve the required geometry. For this research, six representative parts differing in dimension, shape and complexity have been selected.

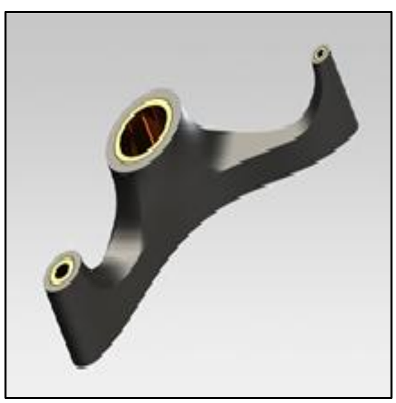


Figure 7 : Bracket (GRABCAD, 2013a)

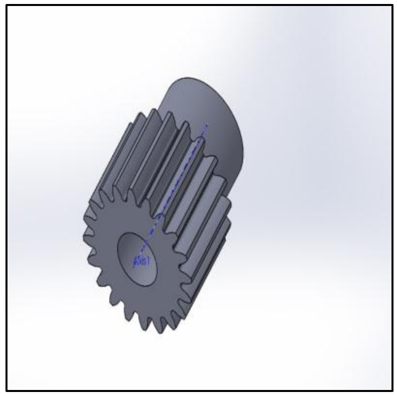


Figure 8 : Gear (GRABCAD, 2013b)

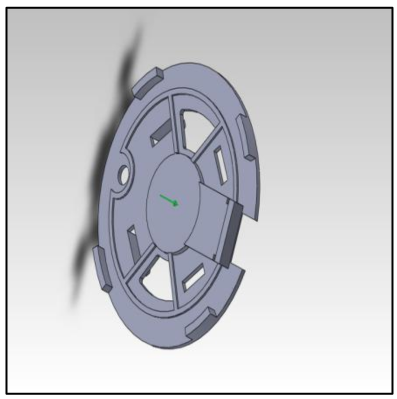


Figure 9 : Horn (GRABCAD, 2013c)

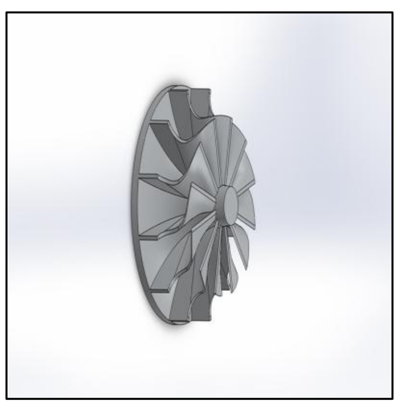


Figure 10 : Impeller (GRABCAD, 2013d)

Figure 11 : Plastic Impeller (GRABCAD, 2013e)

Figure 12 : Spur gear (GRABCAD, 2013f)

The following table summarizes the assumptions of the part complexities for estimating the tool cost for IM:

Table 3 : Part Complexity

Maximum Wall Thickness (in)	0.2
Tolerance (in)	Moderate Precision (≤0.01)
Surface Roughness (μ in)	Normal Polish (Ra ≤ 16)
Complexity	Complex

For the SLS process, the smallest box that is able to contain the part is referred to as the 'bounding box'. In this research, the bounding box volume for each part is calculated by adding 0.5" on each dimension. The smallest dimension is assumed to be the height of the part. The table below summarizes the actual and bounding box dimensions of the parts under consideration.

Table 4: Actual and bounding box dimensions of parts

Part	Length (in)	Breadth (in)	Height (in)	Volume (in^3)	Cross Section (in^2)	Bounding box height (in)	Bounding box volume (in^3)
Spur Gear	1.12	1.12	0.69	0.39	2.6	1.19	3.1
Horn	8.23	8.23	0.7	0.88	76.2	1.20	91.5
Impeller	6.00	6.00	0.9	5.73	42.3	1.40	59.2
Bracket	7.93	5.72	1.63	8.79	52.4	2.13	111.7
Gear	4.34	4.34	2.00	19.36	23.4	2.5	58.6
Plastic Impeller	9.10	9.10	3.94	65.7	92.2	4.44	409.2

5.2 Process Capability and Machine Specification

The following tables summarize the process capabilities for IM and SLS respectively:

Table 5: Process capability of Injection Molding (Custompart.net, 2013a)

Shapes	Thin Walled (Cylindrical, Cubical and Complex)
Part Size (cu.in)	0.01 – 138240
Weight (lbs)	0.03125 – 55
Materials	Thermoplastics, Thermosets, Elastomers
Surface Finish (Ra)	1 – 32 μin
Tolerance (in)	± 0.002
Maximum Wall Thickness (in)	0.015 – 0.5
Quantity	1 – 1000000

Table 6: Process capability of SLS (Custompart.net, 2013b)

Materials	Thermoplastics, Elastomers, Composites
Maximum part size (in)	22.00 x 22.00 x 30.00
Minimum feature size (in)	0.005
Minimum layer thickness (in)	0.004
Tolerance (in)	0.01
Surface finish	Average
Build Speed	Fast

For equations (2) and (3), the parameter values are tabulated below referring to the machine specification manual of the Sinterstation Pro 140 SLS machine:

Table 7: Sinterstation Pro 140 machine specifications (Systems, 2007)

Parameter	Value
Time spent spreading a layer of powder (sec)	22.5
Thickness of powder layer (in)	0.004
Laser scan spacing in the Y direction (in)	0.006
Mirror jump speed (in/sec)	203.2
Mirror scanning speed (in/sec)	240
Mirror stabilization and laser switch delay (sec)	0.0037
Mirror jump delay (sec)	0.002
Roller travel speed (in/sec)	5

5.3 Demand Quantity

The manufacturing process and the mode of transportation to be selected in a *'just in time'* environment depend on the desired lead time and the demand quantity. For this research, a lead time of 7 days is considered. Three levels of demand quantities are considered for this research such as low, medium and high demand. As the tool cost contributes significantly to the unit cost of part manufactured by IM, the demand quantities are calculated as the ratio of opportunity cost of investment in tool per year to the unit cost of part as a percentage of the opportunity cost of investment in tool per year. The rate of return on the investment is assumed to be 30% per annum. The table below lists the unit cost of a part considered as a percentage of the opportunity cost of investment in tool per year for the three levels of demand quantities:

Table 8: Demand levels

Demand Level	Percentage of opportunity cost of investment in tool per year to calculate unit cost of part	No of parts
Low	1%	100
Medium	0.1%	1000
High	0.01%	10000

5.4 Cost and Time Parameters

5.4.1 Material cost

The material to manufacture parts for this study is considered to be nylon. The material cost for nylon SLS powder is considerably higher than the cost of nylon IM pellets. The material specifications used in the time and cost functions for IM and SLS are tabulated below:

Table 9: Material cost and specification (Corporation, 2010) (Custompart.net, 2013a)

Material	Density (lb/in^3)	Thermal diffusivity (in^2/sec)	Material cost ($/lb)	Part ejection temperature (°C)	Mold temperature (°C)	Polymer injection temperature (°C)
Nylon (IM)	0.025	0.000144	3.5	129	91	291
Duraform PA (SLS)	0.036	-	64.2	-	-	-

5.4.2 Machine cost

The machine usage cost for both IM and SLS is calculated as the ratio of total machine utilization time to the total available machine time in the machine depreciation period. It is assumed that the machine utilization rate for both the processes is 70%. The machine cost for IM is estimated to be approximately $300,000 for a reasonably high tonnage press of 200 tons. For this research, the Sinterstation Pro 140 was selected with an assumed cost of $300,000. The table below gives the cost of different SLS machines along with their build capacity and printing speeds:

Table 10: Machine cost and specification (Corporation, 2010)

Machine	Approximate Cost ($)	Cross section of machine bed (in^2)	Maximum machine build volume (in^3)
Sinterstation HiQ	245,888	168	3024
Sinterstation Pro 140	391,916	195	3500
Sinterstation Pro 230	484,447	471	13891

5.4.3 Tool cost

The tool cost is the fixed cost associated with the IM process whereas no tooling is required for the SLS process. The tool cost for the parts under consideration is tabulated below:

Table 11: Tool Cost (Custompart.net, 2013a)

Part	Tool cost ($)
Spur Gear	14,600
Horn	28,900
Impeller	30,700
Bracket	29,300
Gear	32,300
Plastic Impeller	39,700

5.4.4 Energy, labor and inventory costs

According to the Sinterstation Pro 140 specifications, the power requirement for the Sinterstation Pro 140 system is 22 kW. The power requirement for a 200 ton injection molding machine is estimated to be 15 kW, and the energy consumption for a molding cycle is estimated to be 0.04 kWh. The cost of energy consumption was chosen referring to the '*U.S Energy Information Administration (EIA)*' website. The hourly labor wage was chosen referring to the '*United States Department of Labor*' website. The rate of return on investment was assumed to be 30% per annum. The following table summarizes these cost parameters:

Table 12: Rate of Energy, Labor and Storage

Parameter	Value
Rate of energy consumption ($/kW-hour)	0.07
Labor wage ($/hour)	18
Rate of storing inventory ($/cu.in/week)	0.0009
Rate of return on capital invested	30%

5.4.5 Transportation

The transportation cost is a function of the weight of part to be shipped and the service level desired. In the following table, an assumption for the shipping cost per pound is summarized depending on the service level desired.

Table 13: Rate of shipping

Service	Cost ($/lb)
1 Day	5
3 Days	10
5 Days	15

5.4.6 Time

The machine depreciation period was assumed to be 8 years. The pre and post processing time per build for the SLS process and the time to change die was assumed to be 3 hours.

Chapter 6. EXPERIMENTAL RESULTS & ANALYSIS

As proposed in Section 1.3, one of the objectives of this thesis is to find the significant part parameters affecting the unit supply chain cost of parts manufactured by SLS.

6.1 Preliminary Experimental Results

A set of preliminary experiments were run to compare the supply chain costs of the two strategies under consideration. Table 14 shows estimated mold costs for each of the demonstration parts. The third column then lists the opportunity cost associated with investing money in a mold rather than another investment with an assumed return of 30%. The final three columns then show this opportunity cost divided by the number of parts under the low (100), medium (1000), and high (10,000) replacement part demand scenarios. Note that these demand levels pertain specifically to spare/replacement parts rather than production of original run parts.

Table 14: Unit mold cost of parts

Part	Mold Cost ($)	Opportunity cost of investment in tool per year ($)	Opportunity cost per part for low demand ($/part)	Opportunity cost per part for medium demand ($/part)	Opportunity cost per part for high demand ($/part)
Spur Gear	14,600	4,380	44	4	0.04
Horn	28,900	8,670	87	9	0.09
Impeller	30,700	9,210	92	9	0.09
Bracket	29,300	8,790	88	9	0.09
Gear	32,300	9,690	97	10	0.10
Plastic Impeller	39,700	11,910	119	12	0.12

Experiments were run for a planning horizon of 50 time periods for the three demand levels. An average order quantity of 2, 20 and 200 parts per time period for the low, medium and high demand levels was assumed. The unit supply chain cost of parts under consideration for the three demand levels using the supply chain strategy to manufacture by IM and stock to meet future demands is tabulated below:

Table 15: Unit supply chain cost of parts manufactured by IM

Part	Material volume of part (in^3)	Bounding box cross section of part (in^2)	Bounding box height of part (in)	Unit supply chain cost per part for low demand ($/part)	Unit supply chain cost per part for medium demand ($/part)	Unit supply chain cost per part for high demand ($/part)
Spur Gear	0.4	2.6	1.2	44	5	0.9
Horn	0.9	76.2	1.2	87	9	1.5
Impeller	5.7	42.3	1.4	94	11	2.7
Bracket	8.8	52.4	2.1	90	11	3.3
Gear	19.4	23.4	2.5	102	15	6.0
Plastic Impeller	65.7	92.2	4.4	135	28	17

Figures 13, 14 and 15 summarize the breakdown of individual cost components of the unit supply chain cost of parts manufactured by IM for low, medium and high demands respectively.

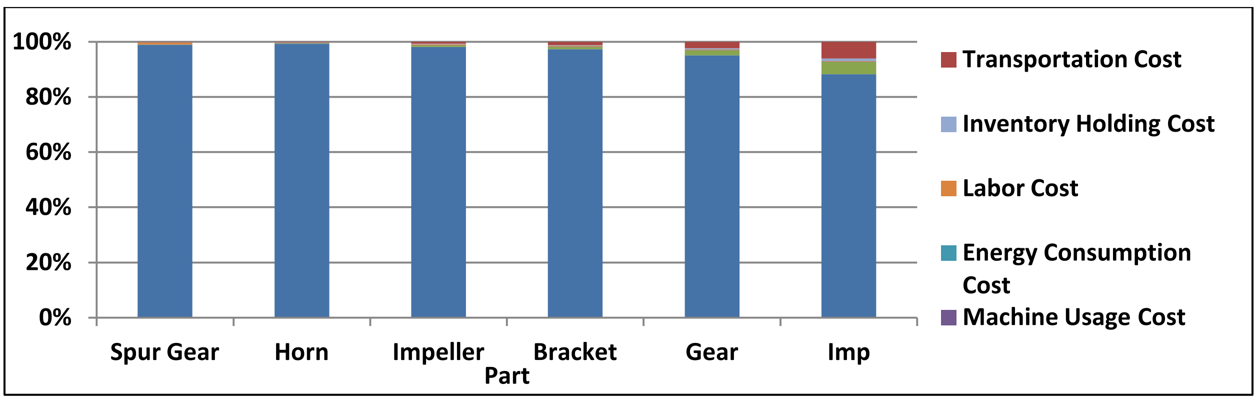


Figure 13: Distribution of costs for low demand manufactured by IM

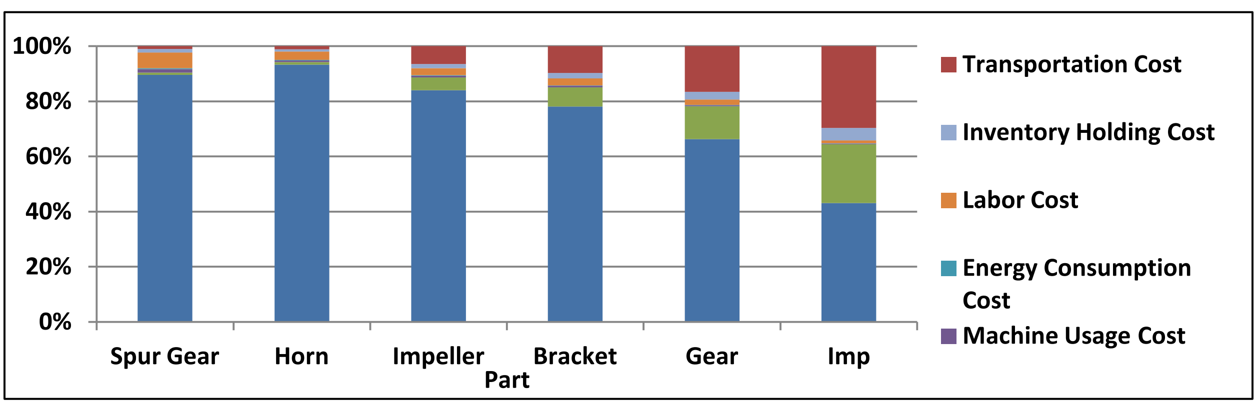


Figure 14: Distribution of costs for medium demand manufactured by IM

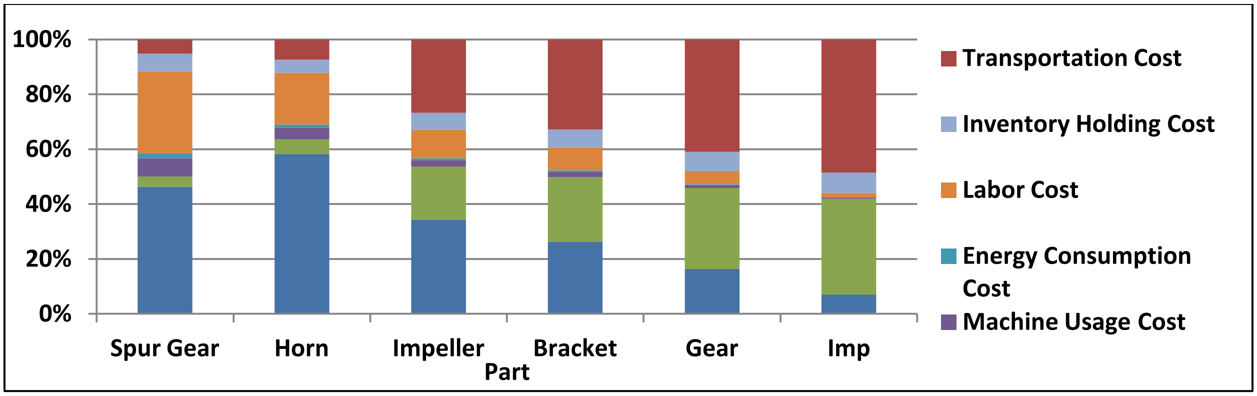


Figure 15: Distribution of costs for high demand manufactured by IM

The unit supply chain cost of parts under consideration for the three demand levels using the JIT production strategy to manufacture in-house by SLS is tabulated below:

Table 16: Unit supply chain cost of parts manufactured in-house by SLS

Part	Material volume of part (in^3)	Bounding box cross section of part (in^2)	Bounding box height of part (in)	Unit supply chain cost per part for low demand ($/part)	Unit supply chain cost per part for medium demand ($/part)	Unit supply chain cost per part for high demand ($/part)
Spur Gear	0.4	2.6	1.2	34	5	3
Horn	0.9	76.2	1.2	42	18	17
Impeller	5.7	42.3	1.4	59	32	30
Bracket	8.8	52.4	2.1	78	51	50
Gear	19.4	23.4	2.5	107	75	73
Plastic Impeller	65.7	92.2	4.4	309	290	289

Figures 16, 17 and 18 summarize the breakdown of individual cost components of the unit supply chain cost of parts manufactured by SLS for low, medium and high demands respectively.

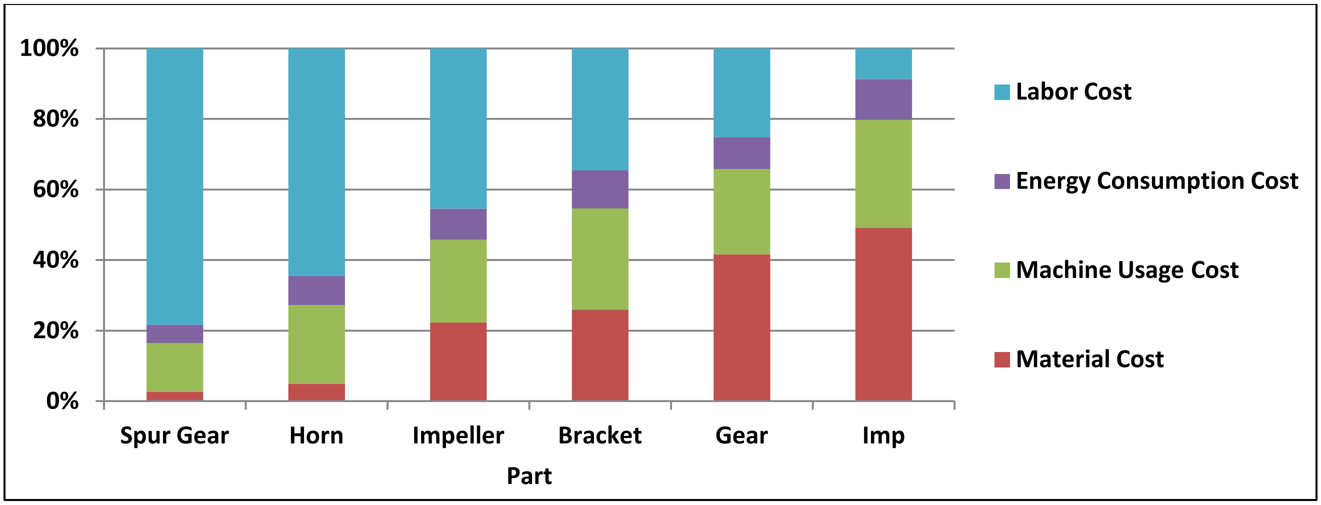


Figure 16: Distribution of costs for low demand manufactured by SLS

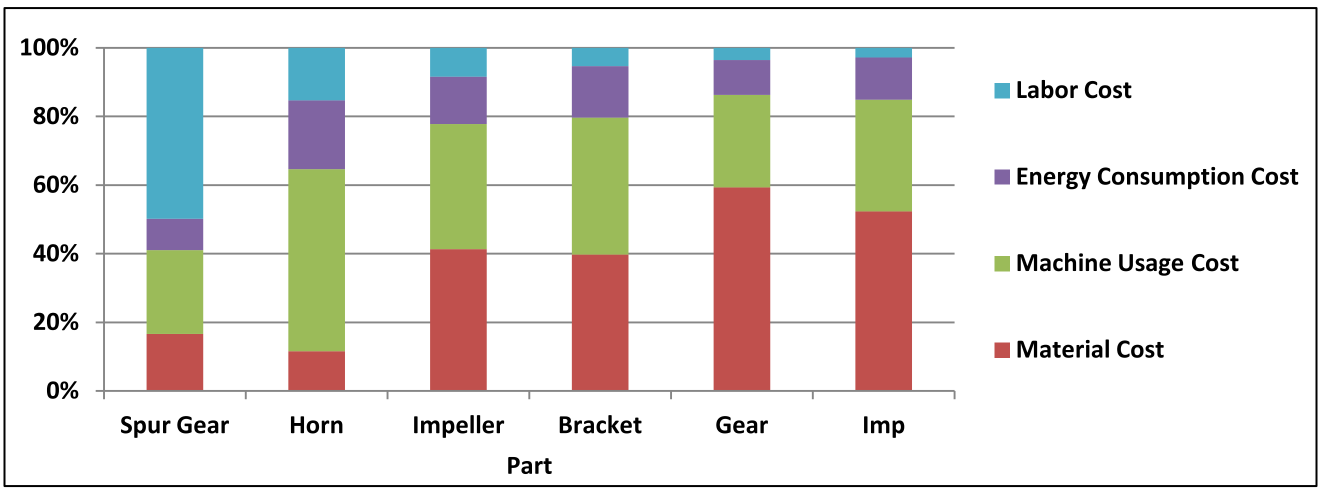


Figure 17: Distribution of costs for medium demand manufactured by SLS

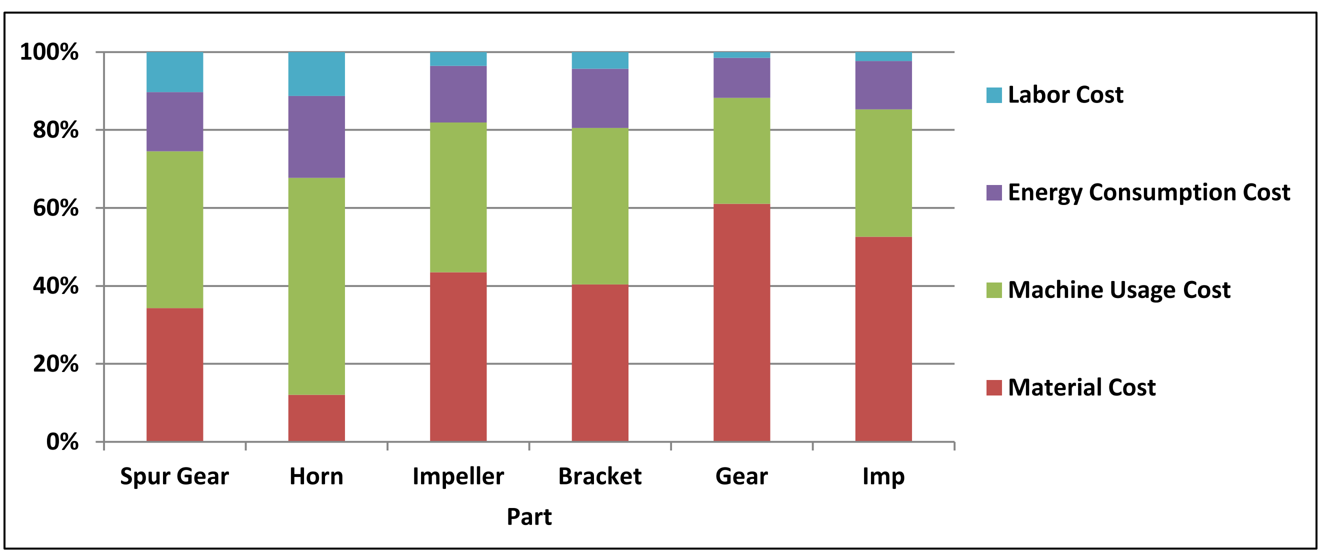


Figure 18: Distribution of costs for high demand manufactured by SLS

Comparing the unit supply chain cost for the two supply chain strategies in Table 15 and Table 16, it can be seen that the supply chain strategy to manufacture by IM and stock to meet future demands is cheaper compared to manufacturing in-house by SLS for medium and high demands for all parts. For the low demand level, the supply chain strategy to manufacture in-house by SLS is cheaper compared to the supply chain strategy to manufacture by IM and stock to meet future demand for certain parts. The breakdown of costs for the unit supply chain costs of parts in Tables 15 and 16 is given in Appendix A.

6.2 Determining Significant Factors and Deriving Regression Equation for Unit Supply Chain Cost of SLS

From the results of the preliminary experiments, it was evident that adopting the supply chain strategy to manufacture in-house by SLS was cheaper for certain parts for low demand compared to the supply chain strategy to manufacture by IM and stock to meet future demands. The costs contributing to the unit cost of parts manufactured by SLS are labor cost, machine utilization cost, energy consumption cost and material cost. The labor cost is the fixed cost while the machine utilization and energy consumption costs are function of the machine working time. The machine working time depends on the part specifications such as the material volume to be sintered, bounding box height and the bounding box cross section of the part. An analysis on the part specifications affecting the unit supply chain cost of parts manufactured by SLS is performed in this section.

Three different levels of part parameters such as the material volume, bounding box cross section and bounding box height of the part were considered for performing experiments. These levels of part parameters were considered as a percentage of the machine specifications. The percentages were selected in reference to the specification of parts considered in the preliminary experiments which were considered as a percentage of the machine specifications. The material volume of the part was considered to be a percentage of the machine build, the bounding box cross-section of the part as a percentage of the cross section of the machine bed and the bounding box height of the part as a percentage of the machine build height. The table below shows the factors and levels for the part specifications as low, medium and high levels considered for this analysis:

Table 17: Levels of part specifications with respect to machine specifications

Factor	Low level	Medium level	High level
A (Material Volume)	0.5% of machine build volume	1% of machine build volume	1.5% of machine build volume
B (Bounding box height)	5% of machine build height	10% of machine build height	15% of machine build height
C (Bounding box cross section)	25% of machine bed cross section	50% of machine bed cross section	75% of machine bed cross section

The results of the experiments obtained from running the mathematical model for the experimental setup in Table 17 are given in Appendix B. Minitab 17 statistical software was used to generate a general full factorial design with three factors and three levels for each factor, for a total of 27 runs. The predictor variables were Factor A (*Material Volume*), Factor B (*Bounding Box Height of Part*) and Factor C (*Bounding Box Cross Section of Part*). A regression model was run with Factor A (*Material Volume*), Factor B (*Bounding Box Height of Part*), Factor C (*Bounding Box Cross Section of Part*), the interaction of factors A & B (*Material Volume & Bounding Box Height of Part*), the interaction of factors B & C (*Bounding Box Height of Part & Bounding Box Cross Section of Part),* the interaction of factors A & C (*Material Volume & Bounding Box Cross Section of Part)* and interaction of factors A, B & C (*Material Volume, Bounding Box Cross Height of Part & Bounding Box Cross Section of Part).* The unit supply chain cost of part for the supply chain strategy to manufacture in-house by SLS was the response variable. The ANOVA for the model is provided in Figure 19.

```
Analysis of Variance

Source                                                           DF   Adj SS    Adj MS
Regression                                                        7  26300.8   3757.26
  Material Volume                                                 1    120.7    120.68
  Bounding Box Cross Section                                      1      0.2      0.22
  Bounding Box Height                                             1     32.9     32.90
  Material Volume*Bounding Box Cross Section                      1     11.9     11.90
  Material Volume*Bounding Box Height                             1     11.7     11.66
  Bounding Box Cross Section*Bounding Box Height                  1      1.9      1.94
  Material Volume*Bounding Box Cross Section*Bounding Box Height  1      0.0      0.01
Error                                                            21     68.7      3.27
  Lack-of-Fit                                                    19     68.7      3.62
  Pure Error                                                      2      0.0      0.00
Total                                                            28  26369.5

Source                                                           F-Value  P-Value
Regression                                                       1148.56    0.000
  Material Volume                                                  36.89    0.000
  Bounding Box Cross Section                                        0.07    0.799
  Bounding Box Height                                              10.06    0.005
  Material Volume*Bounding Box Cross Section                        3.64    0.070
  Material Volume*Bounding Box Height                               3.56    0.073
  Bounding Box Cross Section*Bounding Box Height                    0.59    0.450
  Material Volume*Bounding Box Cross Section*Bounding Box Height    0.00    0.954
Error
  Lack-of-Fit                                                          *        *
  Pure Error
Total


Model Summary

      S    R-sq  R-sq(adj)  R-sq(pred)
1.80867  99.74%     99.65%      99.29%
```

Figure 19: Analysis of variance for the full regression model

From the ANOVA in Figure 19, it is clear that factors A (*Material Volume)* and B (*Bounding Box Height of Part*) were significant with a p-value less than 0.05. The model was further improved by eliminating the terms having the highest p-value using the backward elimination method. The three way interaction between Factor A (*Material Volume*), Factor B (*Bounding Box Height of Part*) and Factor C (*Bounding Box Cross Section of Part*) was removed from the model as it had the highest p-value (0.954). Figure 20 shows the ANOVA for the reduced model.

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	6	26300.8	4383.47	1403.57	0.000
Material Volume	1	455.4	455.37	145.81	0.000
Bounding Box Cross Section	1	0.7	0.68	0.22	0.644
Bounding Box Height	1	161.7	161.72	51.78	0.000
Material Volume*Bounding Box Cross Section	1	77.3	77.27	24.74	0.000
Material Volume*Bounding Box Height	1	71.7	71.68	22.95	0.000
Bounding Box Cross Section*Bounding Box Height	1	22.7	22.75	7.28	0.013
Error	22	68.7	3.12		
Lack-of-Fit	20	68.7	3.44	*	*
Pure Error	2	0.0	0.00		
Total	28	26369.5			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
1.76723	99.74%	99.67%	99.49%

Figure 20: Analysis of variance for the reduced model

From Figures 19 and 20, the elimination of the three way interaction resulted in an increase in the R^2 value from 99.65% to 99.67%. Referring Figure 21, the 'Residuals Versus Fits' plot did not indicate abnormalities in the variance, satisfying the assumption of equal variance. The 'Residuals Versus Order' plot did not exhibit a particular pattern satisfying the assumption of independence of the ANOVA model. The Normal distribution of variances was verified using the Anderson-Darling test of normality. Figure 22 shows the normal probability plot with a p-value of 0.303 which is greater than the significance level of 0.05.

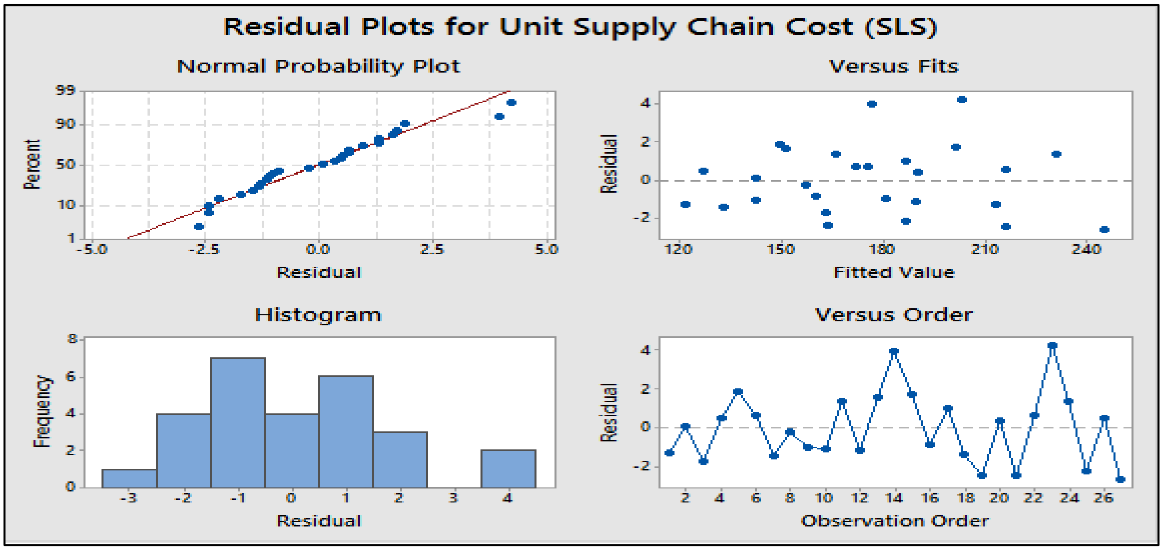


Figure 21: Residual Plots for unit supply chain cost for SLS

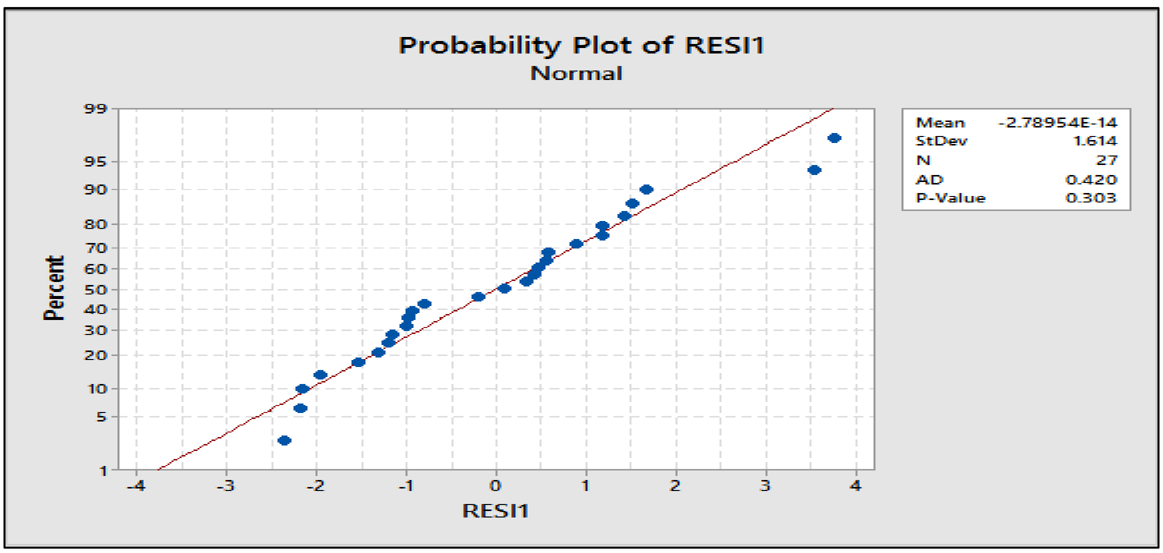


Figure 22: Normality test for residuals from unit supply chain cost for SLS

The regression equation to predict the unit supply chain cost of parts manufactured in-house by SLS was as follows:

```
Regression Equation

Model Cost = 62.49 + 1.884 Material Volume - 0.0165 Bounding Box Cross Section
             + 13.99 Bounding Box Height + 0.00562 Material Volume*Bounding Box Cross Section
             + 0.3010 Material Volume*Bounding Box Height
             + 0.0304 Bounding Box Cross Section*Bounding Box Height
```

Figure 23: Regression equation for predicting unit supply chain cost of parts manufactured in-house using SLS

The detailed Minitab output of the full model, reduced model, residual and normality plots of the reduced model are given in Appendix C.

6.3 Validation Experiments for the Regression Equation

A set of experiments were carried out to validate the regression equation derived in Section 6.2. The levels for the predictors Material Volume, Bounding Box Height and Bounding Box Cross Section of the part were considered to be percentages of the machine specifications. The machine specifications are tabulated in Table 10. The table below summarizes the levels considered for the predictors:

Table 18: Setup for validation experiments

Bounding Box Height (% of Machine Height)	Bounding Box Height (in)	Material Volume (% of Machine build)	Material Volume (in^3)	Bounding Box Cross Section (% of Cross Section of Machine bed)	Bounding Box Cross Section (in^2)
7.5	1.4	0.01	0.4	70	137
22.5	4.1	0.25	8.8	80	156
30	5.4	0.75	26.3	90	176
37.5	6.8	2.5	87.5	-	-
52.5	9.5	-	-	-	-
60	10.8	-	-	-	-

The unit supply chain cost predicted by the regression equation in Figure 23 was compared with the values obtained from the mathematical model. The breakdown of costs for the experimental setup in Table 18 is given in Appendix D. The error in the values obtained from the mathematical model and regression equation was calculated using Mean Absolute Percentage Error (MAPE) as follows:

$$\mathbf{MAPE} = \frac{\sum_{1}^{n}\left[\frac{abs(Model\ Cost - Predicted\ Cost)}{Model\ Cost} * 100\right]}{n}$$

Table 19 summarizes the results. The MAPE was calculated to be 7%.

Table 19: Summary of validation experiments

Bound Box Height (in)	Material Volume (in^3)	Bounding Box Cross Section (in^2)	Unit Supply Chain Cost (Mathematical Model)	Unit Supply Chain Cost (Regression Equation)	Absolute Percentage Error (APE)
1.4	0.4	136.5	79	87	10
1.4	0.4	156	80	87	10
1.4	0.4	175.5	80	88	10
1.4	8.8	136.5	110	113	3
1.4	8.8	156	111	114	3
1.4	8.8	175.5	112	116	4
1.4	26.3	136.5	168	166	1
1.4	26.3	156	170	170	0
1.4	26.3	175.5	172	173	1
1.4	87.5	136.5	335	354	6
1.4	87.5	156	341	365	7
1.4	87.5	175.5	347	375	8
4.1	0.4	136.5	136	136	0
4.1	0.4	156	139	138	0
4.1	0.4	175.5	141	140	1
4.1	8.8	136.5	167	169	1
4.1	8.8	156	171	172	1
4.1	8.8	175.5	173	175	1
4.1	26.3	136.5	231	237	2
4.1	26.3	156	235	242	3
4.1	26.3	175.5	238	247	4
4.1	87.5	136.5	432	475	10
4.1	87.5	156	439	486	11
4.1	87.5	175.5	445	498	12
5.4	0.4	136.5	163	160	2
5.4	0.4	156	167	163	3
5.4	0.4	175.5	171	166	3
5.4	8.8	136.5	195	196	0
5.4	8.8	156	199	200	0
5.4	8.8	175.5	203	204	0
5.4	26.3	136.5	260	271	4
5.4	26.3	156	264	276	5
5.4	26.3	175.5	268	282	5
5.4	87.5	136.5	467	532	14
5.4	87.5	156	475	545	15
5.4	87.5	175.5	481	557	16
6.8	0.4	136.5	192	185	4
6.8	0.4	156	198	189	4
6.8	0.4	175.5	203	193	5
6.8	8.8	136.5	224	225	0

6.8	8.8	156	230	230	0
6.8	8.8	175.5	235	234	0
6.8	26.3	136.5	290	307	6
6.8	26.3	156	296	314	6
6.8	26.3	175.5	301	320	7
6.8	87.5	136.5	502	595	18
6.8	87.5	156	511	608	19
6.8	87.5	175.5	518	621	20
9.5	0.4	136.5	249	235	6
9.5	0.4	156	257	240	7
9.5	0.4	175.5	264	245	7
9.5	8.8	136.5	281	281	0
9.5	8.8	156	289	287	1
9.5	8.8	175.5	296	294	1
9.5	26.3	136.5	347	377	9
9.5	26.3	156	355	386	9
9.5	26.3	175.5	362	394	9
9.5	87.5	136.5	566	715	26
9.5	87.5	156	576	730	27
9.5	87.5	175.5	584	745	27
10.8	0.4	136.5	276	259	6
10.8	0.4	156	285	265	7
10.8	0.4	175.5	293	271	8
10.8	8.8	136.5	309	308	0
10.8	8.8	156	318	315	1
10.8	8.8	175.5	325	322	1
10.8	26.3	136.5	375	411	10
10.8	26.3	156	384	420	9
10.8	26.3	175.5	392	429	10
10.8	87.5	136.5	595	773	30
10.8	87.5	156	606	788	30
10.8	87.5	175.5	616	804	31

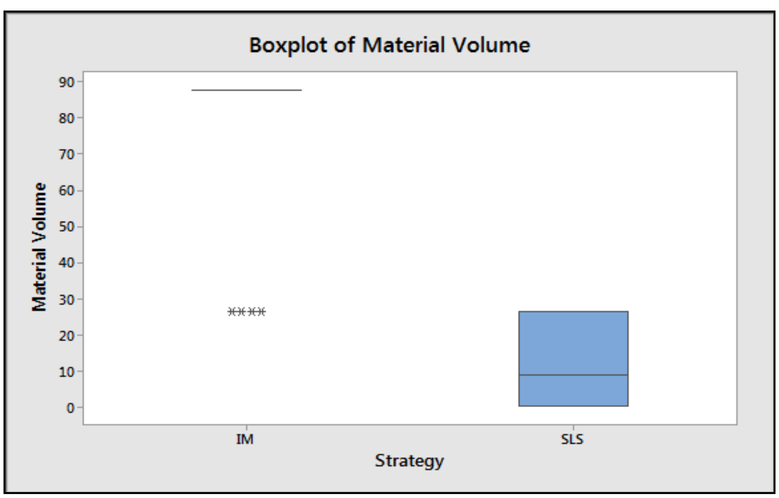
The unit supply chain cost of parts for the supply chain strategy to manufacture at a central location using IM and stock to meet future needs for the setup in Table 18 was determined using the mathematical model. The model was run considering a planning horizon of 50 time periods with an average demand of 1 part per time period. The breakdown of IM costs obtained from the mathematical model for the experimental setup in Table 18 is given in Appendix D. The unit supply chain for the two supply chain strategies under consideration have been tabulated below:

Table 20: Unit supply chain cost for the two supply chain strategies under consideration

Bound Box Height (in)	Material Volume (in^3)	Bounding Box Cross Section (in^2)	Unit Supply Chain Cost ($) (SLS)	Unit Supply Chain Cost ($) (IM)	Strategy
1.4	0.4	136.5	79	291	SLS
1.4	0.4	156	80	304	SLS
1.4	0.4	175.5	80	316	SLS
1.4	8.8	136.5	110	293	SLS
1.4	8.8	156	111	306	SLS
1.4	8.8	175.5	112	318	SLS
1.4	26.3	136.5	168	297	SLS
1.4	26.3	156	170	310	SLS
1.4	26.3	175.5	172	322	SLS
1.4	87.5	136.5	335	311	IM
1.4	87.5	156	341	324	IM
1.4	87.5	175.5	347	336	IM
4.1	0.4	136.5	136	297	SLS
4.1	0.4	156	139	310	SLS
4.1	0.4	175.5	141	327	SLS
4.1	8.8	136.5	167	299	SLS
4.1	8.8	156	171	312	SLS
4.1	8.8	175.5	173	329	SLS
4.1	26.3	136.5	231	304	SLS
4.1	26.3	156	235	316	SLS
4.1	26.3	175.5	238	333	SLS
4.1	87.5	136.5	432	318	IM
4.1	87.5	156	439	331	IM
4.1	87.5	175.5	445	348	IM
5.4	0.4	136.5	163	305	SLS
5.4	0.4	156	167	324	SLS
5.4	0.4	175.5	171	337	SLS
5.4	8.8	136.5	195	307	SLS
5.4	8.8	156	199	326	SLS
5.4	8.8	175.5	203	339	SLS
5.4	26.3	136.5	260	311	SLS
5.4	26.3	156	264	330	SLS
5.4	26.3	175.5	268	343	SLS
5.4	87.5	136.5	467	325	IM
5.4	87.5	156	475	344	IM
5.4	87.5	175.5	481	357	IM
6.8	0.4	136.5	192	313	SLS
6.8	0.4	156	198	326	SLS
6.8	0.4	175.5	203	350	SLS
6.8	8.8	136.5	224	314	SLS
6.8	8.8	156	230	328	SLS
6.8	8.8	175.5	235	352	SLS
6.8	26.3	136.5	290	319	SLS
6.8	26.3	156	296	332	SLS
6.8	26.3	175.5	301	356	SLS
6.8	87.5	136.5	502	333	IM
6.8	87.5	156	511	347	IM
6.8	87.5	175.5	518	370	IM

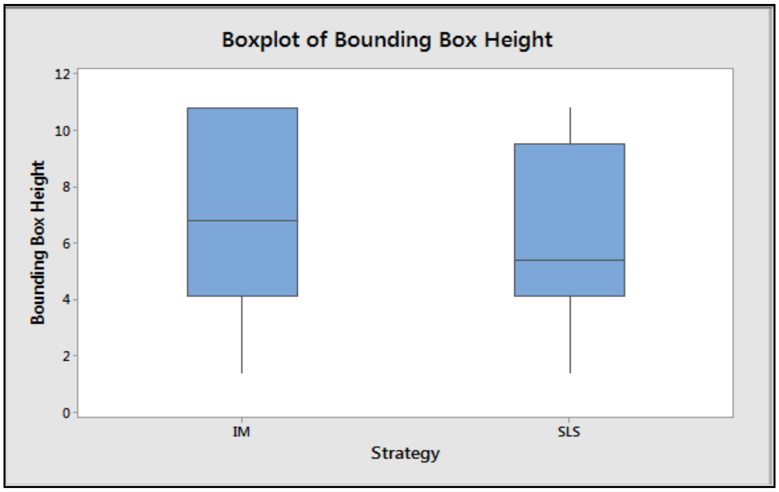
9.5	0.4	136.5	249	326	SLS
9.5	0.4	156	257	353	SLS
9.5	0.4	175.5	264	366	SLS
9.5	8.8	136.5	281	328	SLS
9.5	8.8	156	289	355	SLS
9.5	8.8	175.5	296	368	SLS
9.5	26.3	136.5	347	332	IM
9.5	26.3	156	355	359	SLS
9.5	26.3	175.5	362	372	SLS
9.5	87.5	136.5	566	347	IM
9.5	87.5	156	576	373	IM
9.5	87.5	175.5	584	386	IM
10.8	0.4	136.5	276	329	SLS
10.8	0.4	156	285	356	SLS
10.8	0.4	175.5	293	369	SLS
10.8	8.8	136.5	309	331	SLS
10.8	8.8	156	318	358	SLS
10.8	8.8	175.5	325	371	SLS
10.8	26.3	136.5	375	335	IM
10.8	26.3	156	384	362	IM
10.8	26.3	175.5	392	375	IM
10.8	87.5	136.5	595	349	IM
10.8	87.5	156	606	376	IM
10.8	87.5	175.5	616	389	IM

The Box plots below show the cost effectiveness of opting for a particular supply chain strategy depending on the three factors Material Volume, Bounding Box Height and Bounding Box Cross Section of the part.



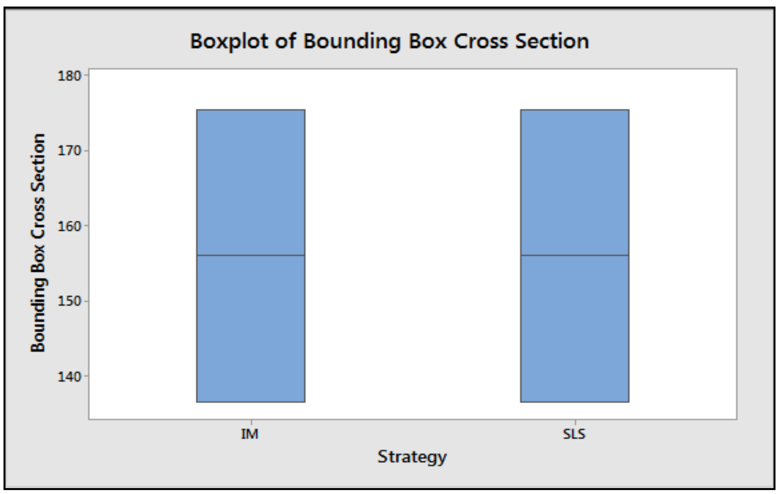
	IM	SLS
Q1	87.5	0.4
Median	87.5	8.8
Q3	87.5	26.3
IQR	0	25.9
Whiskers	87.5, 87.5	0.4, 26.3
N	22	50

Figure 24: Box plot of material volume vs supply chain strategy



	IM	SLS
Q1	4.1	4.1
Median	6.8	5.4
Q3	10.8	9.5
IQR	6.7	5.4
Whiskers	1.4, 10.8	1.4, 10.8
N	22	50

Figure 25: Box plot of bounding box height vs supply chain strategy

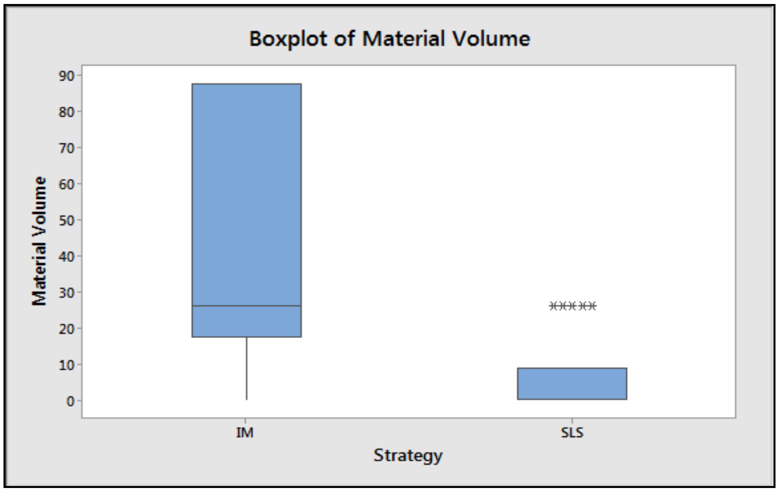


	IM	SLS
Q1	136.5	136.5
Median	156	156
Q3	175.5	175.5
IQR	39	39
Whiskers	136.5, 175.5	136.5, 175.5
N	22	50

Figure 26: Box plot of bounding box cross section vs supply chain strategy

From the Box plots in Figures 24, 25 and 26, it is evident that the supply chain strategy to manufacture on demand site using SLS is cheaper compared to the supply chain strategy to manufacture by IM except for parts with the highest level of material volume 87.5 in^3 (2.5% of the machine build). The Bounding Box Height and Bounding Box Cross Section of part do not favor a particular supply chain strategy.

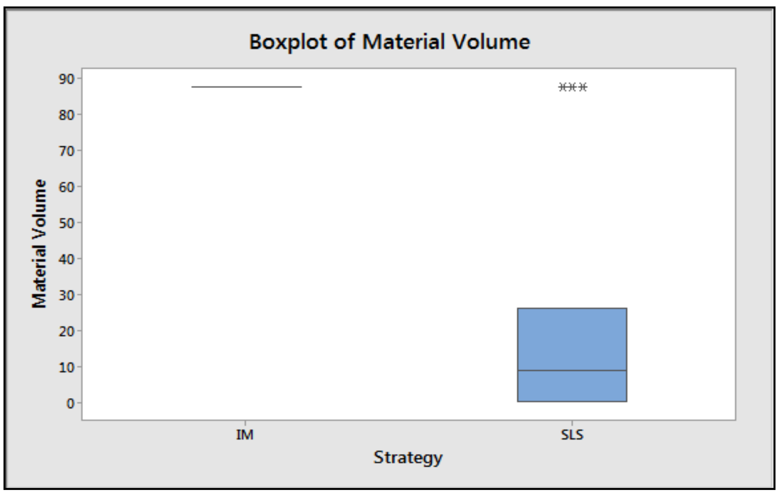
The effect of tool cost for IM on the supply chain strategy was carried out by varying the cost of the tool by 25%. The Box plot in Figure 27 shows that if the tool cost is reduced by 25%, then IM becomes the more economical supply chain strategy for parts with high material volume.



	IM	SLS
Q1	17.5	0.4
Median	26.3	8.8
Q3	87.5	8.8
IQR	69.95	8.4
Whiskers	0.4, 87.5	0.4, 8.8
N	41	31

Figure 27: Box plot of material volume vs supply chain strategy when tool cost reduces

The Box plot in Figure 28 shows that if the tool cost increases by 25%, SLS becomes the preferred supply chain strategy for parts with low material volume.



	IM	SLS
Q1	87.5	0.4
Median	87.5	8.8
Q3	87.5	26.3
IQR	0	25.9
Whiskers	87.5, 87.5	0.4, 26.3
N	15	57

Figure 28: Box plot of material volume vs supply chain strategy when tool cost increase

Chapter 7. CONCLUSIONS & FUTURE WORK

A detailed model showing the conditions under which low part demands are economically satisfied using on-demand SLS manufacturing rather than conventional injection molding was developed. The part specification contributing significantly to the supply chain cost of parts manufactured by SLS were determined using regression analysis. Material Volume, Part Bounding Box Height, and the two way interactions between Material Volume, Bounding Box Height, and Part Bounding Box Cross Section proved to be the significant factors. A regression equation to predict the unit supply chain cost of parts manufactured in-house was derived and validated with a MAPE of 7%. From the box plot in Figure 24, it can be said that parts having low material volume relative to the machine build are cheaper to produce via SLS than manufacturing by IM, particularly when part quantities are low. The tool cost for IM plays a significant role in the decision making process and is illustrated in Figures 27 and 28.

In this research, the cost of molds was referenced from an online source (Custompart.net). An equation to predict the unit supply chain cost of a part manufactured by IM can be derived considering part specifications and complexities. An equation predicting the cheaper supply chain strategy considering supply chain parameters such as lead time, part specifications and demand quantity can be an interesting area of study. The mathematical model developed in this research to estimate the economical supply chain strategy with respect to part parameters can be used to optimize the supply chain as a future work.

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Appendix A: Results from the mathematical model for preliminary experiments

Part	Material Cost ($)	Machine Usage Cost ($)	Energy Consumption Cost ($)	Labor Cost ($)	Unit supply chain cost of part for low demand ($)
Spur Gear	1	5	2	27	34
Horn	2	9	4	27	42
Impeller	13	14	5	27	59
Bracket	20	22	8	27	78
Gear	45	26	10	27	107
Plastic Impeller	152	94	36	27	309

Costs of parts manufactured by SLS in-house (low demand)

Part	Material Cost ($)	Machine Usage Cost ($)	Energy Consumption Cost ($)	Labor Cost ($)	Unit supply chain cost of part for medium demand ($)
Spur Gear	1	1	0	3	5
Horn	2	9	4	3	18
Impeller	13	12	4	3	32
Bracket	20	20	8	3	51
Gear	45	20	8	3	75
Plastic Impeller	152	94	36	8	290

Costs of parts manufactured by SLS in-house (medium demand)

Part	Material Cost ($)	Machine Usage Cost ($)	Energy Consumption Cost ($)	Labor Cost ($)	Unit supply chain cost of part for high demand ($)
Spur Gear	1	1	0	0	3
Horn	2	9	4	2	17
Impeller	13	12	4	1	30
Bracket	20	20	8	2	50
Gear	45	20	8	1	73
Plastic Impeller	152	94	36	7	289

Costs of parts manufactured by SLS in-house (high demand)

Part	Mold Cost ($)	Material Cost ($)	Machine Usage Cost ($)	Energy Consumption Cost ($)	Labor Cost ($)	Inventory Holding Cost ($)	Transportation Cost ($)	Unit supply chain cost of part for low demand ($)
Spur Gear	44	0	0.06	0.02	0.28	0.06	0.05	44
Horn	87	0	0.06	0.02	0.28	0.07	0.11	87
Impeller	92	1	0.06	0.02	0.28	0.16	0.72	94
Bracket	88	1	0.06	0.02	0.28	0.22	1.10	90
Gear	97	2	0.06	0.02	0.28	0.41	2.42	102
Plastic Impeller	119	6	0.06	0.02	0.28	1.26	8.21	135

Costs of parts manufactured by IM at central location (low demand)

Part	Mold Cost ($)	Material Cost ($)	Machine Usage Cost ($)	Energy Consumption Cost ($)	Labor Cost ($)	Inventory Holding Cost ($)	Transportation Cost ($)	Unit supply chain cost of part for medium demand ($)
Spur Gear	4	0	0.06	0.02	0.28	0.06	0.05	5
Horn	9	0	0.06	0.02	0.28	0.07	0.11	9
Impeller	9	1	0.06	0.02	0.28	0.16	0.72	11
Bracket	9	1	0.06	0.02	0.28	0.22	1.10	11
Gear	10	2	0.06	0.02	0.28	0.41	2.42	15
Plastic Impeller	12	6	0.06	0.02	0.28	1.26	8.21	28

Costs of parts manufactured by IM at central location (medium demand)

Part	Mold Cost ($)	Material Cost ($)	Machine Usage Cost ($)	Energy Consumption Cost ($)	Labor Cost ($)	Inventory Holding Cost ($)	Transportation Cost ($)	Unit supply chain cost of part for high demand ($)
Spur Gear	0.4	0.04	0.06	0.02	0.28	0.06	0.05	0.9
Horn	0.9	0.08	0.06	0.02	0.28	0.07	0.11	1.5
Impeller	0.9	0.52	0.06	0.02	0.28	0.16	0.72	2.7
Bracket	0.9	0.79	0.06	0.02	0.28	0.22	1.10	3.3
Gear	1.0	1.74	0.06	0.02	0.28	0.41	2.42	5.9
Plastic Impeller	1.2	5.92	0.06	0.02	0.28	1.26	8.21	17

Costs of parts manufactured by IM at central location (high demand)

Appendix B: Results from the mathematical model for experimental setup in Table 17

Material Volume (in^3)	Bounding Box Cross Section of part (in^2)	Bounding Box Height of part (in)	Material Cost ($)	Machine usage Cost ($)	Energy Consumption Cost ($)	Labor Cost ($)	Unit Supply Chain Cost ($)
17.5	48.75	0.9	40.4	16.8	6	54	118
17.5	48.75	1.8	40.4	31.5	12	54	137
17.5	48.75	2.7	40.4	44.0	16	54	155
17.5	97.5	0.9	40.4	21.6	8	54	123
17.5	97.5	1.8	40.4	37.4	14	54	143
17.5	97.5	2.7	40.4	51.3	19	54	163
17.5	146.25	0.9	40.4	24.2	9	54	129
17.5	146.25	1.8	40.4	40.8	15	54	150
17.5	146.25	2.7	40.4	56.1	21	54	171
26.25	48.75	0.9	60.7	17.5	7	54	139
26.25	48.75	1.8	60.7	34.6	13	54	160
26.25	48.75	2.7	60.7	48.6	18	54	181
26.25	97.5	0.9	60.7	24.7	9	54	147
26.25	97.5	1.8	60.7	42.9	16	54	169
26.25	97.5	2.7	60.7	58.0	22	54	192
26.25	146.25	0.9	60.7	28.7	11	54	155
26.25	146.25	1.8	60.7	47.5	18	54	179
26.25	146.25	2.7	60.7	63.6	24	54	202
35	48.75	0.9	80.9	17.3	7	54	161
35	48.75	1.8	80.9	36.5	14	54	184
35	48.75	2.7	80.9	51.9	19	54	207
35	97.5	0.9	80.9	26.6	10	54	171
35	97.5	1.8	80.9	47.3	18	54	195
35	97.5	2.7	80.9	63.7	24	54	220
35	146.25	0.9	80.9	32.0	12	54	181
35	146.25	1.8	80.9	53.2	20	54	207
35	146.25	2.7	80.9	70.4	26	54	233

Costs of parts manufactured by SLS in-house

Appendix C: Minitab Output

Minitab Output for Full model

Regression Analysis: Model Cost versus Material Volume, Bounding Box Cross section, Bounding Box Height

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	7	26300.8	3757.26	1148.56	0.000
Material Volume	1	120.7	120.68	36.89	0.000
Bounding Box Cross Section	1	0.2	0.22	0.07	0.799
Bounding Box Height	1	32.9	32.90	10.06	0.005
Material Volume*Bounding Box Cross Section	1	11.9	11.90	3.64	0.070
Material Volume*Bounding Box Height	1	11.7	11.66	3.56	0.073
Bounding Box Cross Section*Bounding Box Height	1	1.9	1.94	0.59	0.450
Material Volume*Bounding Box Cross Section*Bounding Box Height	1	0.0	0.01	0.00	0.954
Error	21	68.7	3.27		
Lack-of-Fit	19	68.7	3.62	*	*
Pure Error	2	0.0	0.00		
Total	28	26369.5			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
1.80867	99.74%	99.65%	99.29%

Coefficients

Term	Coef	SE Coef	T-Value
Constant	62.88	7.99	7.88
Material Volume	1.868	0.308	6.07
Bounding Box Cross Section	-0.0207	0.0803	-0.26
Bounding Box Height	13.77	4.34	3.17
Material Volume*Bounding Box Cross Section	0.00579	0.00303	1.91
Material Volume*Bounding Box Height	0.310	0.164	1.89

Bounding Box Cross Section*Bounding Box Height	0.0329	0.0427	0.77
Material Volume*Bounding Box Cross Section*Bounding Box Height	-0.00009	0.00160	-0.06

Term	P-Value	VIF
Constant	0.000	
Material Volume	0.000	43.99
Bounding Box Cross Section	0.799	92.94
Bounding Box Height	0.005	88.49
Material Volume*Bounding Box Cross Section	0.070	141.20
Material Volume*Bounding Box Height	0.073	135.28
Bounding Box Cross Section*Bounding Box Height	0.450	180.16
Material Volume*Bounding Box Cross Section*Bounding Box Height	0.954	223.77

Regression Equation

```
Model Cost = 62.88 + 1.868 Material Volume - 0.0207 Bounding Box Cross Section
             + 13.77 Bounding Box Height
+ 0.00579 Material Volume*Bounding Box Cross Section
             + 0.310 Material Volume*Bounding Box Height
             + 0.0329 Bounding Box Cross Section*Bounding Box Height
             - 0.00009 Material Volume*Bounding Box Cross Section*Bounding Box Height
```

Fits and Diagnostics for Unusual Observations

Obs	Model Cost	Fit	Resid	Std Resid	
14	173.048	169.483	3.565	2.01	R
23	199.259	195.506	3.753	2.18	R

R Large residual

Minitab Output for Reduced model

Regression Analysis: Model Cost versus Material Volume, Bounding Box Cross Section, Bounding Box Height

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	6	26300.8	4383.47	1403.57	0.000
Material Volume	1	455.4	455.37	145.81	0.000
Bounding Box Cross Section	1	0.7	0.68	0.22	0.644
Bounding Box Height	1	161.7	161.72	51.78	0.000
Material Volume*Bounding Box Cross Section	1	77.3	77.27	24.74	0.000
Material Volume*Bounding Box Height	1	71.7	71.68	22.95	0.000
Bounding Box Cross Section*Bounding Box Height	1	22.7	22.75	7.28	0.013
Error	22	68.7	3.12		

```
  Lack-of-Fit                                     20     68.7     3.44        *
*
  Pure Error                                       2      0.0     0.00
Total                                             28  26369.5


Model Summary

      S    R-sq  R-sq(adj)  R-sq(pred)
1.76723  99.74%     99.67%      99.49%


Coefficients

Term                                               Coef  SE Coef  T-Value  P-Value
VIF
Constant                                          62.49     4.31    14.50    0.000
Material Volume                                   1.884    0.156    12.08    0.000
11.85
Bounding Box Cross Section                      -0.0165   0.0352    -0.47    0.644
18.69
Bounding Box Height                               13.99     1.94     7.20    0.000
18.60
Material Volume*Bounding Box Cross Section      0.00562  0.00113     4.97    0.000
20.53
Material Volume*Bounding Box Height              0.3010   0.0628     4.79    0.000
20.76
Bounding Box Cross Section*Bounding Box Height   0.0304   0.0113     2.70    0.013
13.18


Regression Equation

Model Cost = 62.49 + 1.884 Material Volume - 0.0165 Bounding Box Cross Section
             + 13.99 Bounding Box Height
+ 0.00562 Material Volume*Bounding Box Cross Section
             + 0.3010 Material Volume*Bounding Box Height
             + 0.0304 Bounding Box Cross Section*Bounding Box Height


Fits and Diagnostics for Unusual Observations

                                     Std
Obs  Model Cost      Fit  Resid  Resid
 14     173.048  169.484  3.564   2.05  R
 23     199.259  195.505  3.753   2.23  R

R  Large residual
```

Appendix D: Results from the mathematical model for experimental setup in Table 18

Bounding Box Height of part (in)	Material Volume of part (in^3)	Bounding Box Cross Section of part (in^2)	Material Cost ($)	Machine usage Cost ($)	Energy Consumption Cost ($)	Labor Cost ($)	Unit Supply Chain Cost ($)
1.4	0.4	136.5	0.9	17.3	7	54	79
1.4	0.4	156	0.9	17.9	7	54	80
1.4	0.4	175.5	0.9	18.4	7	54	80
1.4	8.8	136.5	20.3	25.8	10	54	110
1.4	8.8	156	20.3	26.5	10	54	111
1.4	8.8	175.5	20.3	27.1	10	54	112
1.4	26.3	136.5	60.8	38.6	15	54	168
1.4	26.3	156	60.8	40	15	54	170
1.4	26.3	175.5	60.8	41.2	16	54	172
1.4	87.5	136.5	202.2	56.9	21	54	335
1.4	87.5	156	202.2	61.5	23	54	341
1.4	87.5	175.5	202.2	65.7	25	54	347
4.1	0.4	136.5	0.9	58.5	22	54	136
4.1	0.4	156	0.9	60.8	23	54	139
4.1	0.4	175.5	0.9	62.8	24	54	141
4.1	8.8	136.5	20.3	67.6	26	54	167
4.1	8.8	156	20.3	69.9	26	54	171
4.1	8.8	175.5	20.3	72	27	54	173
4.1	26.3	136.5	60.8	84.6	32	54	231
4.1	26.3	156	60.8	87.2	33	54	235
4.1	26.3	175.5	60.8	89.5	34	54	238
4.1	87.5	136.5	202.2	127.7	48	54	432
4.1	87.5	156	202.2	132.8	50	54	439
4.1	87.5	175.5	202.2	137.2	52	54	445
5.4	0.4	136.5	0.9	78.4	30	54	163
5.4	0.4	156	0.9	81.5	31	54	167
5.4	0.4	175.5	0.9	84.2	32	54	171
5.4	8.8	136.5	20.3	87.5	33	54	195
5.4	8.8	156	20.3	90.7	34	54	199
5.4	8.8	175.5	20.3	93.4	35	54	203
5.4	26.3	136.5	60.8	105.1	40	54	260
5.4	26.3	156	60.8	108.5	41	54	264
5.4	26.3	175.5	60.8	111.5	42	54	268
5.4	87.5	136.5	202.2	153.2	58	54	467
5.4	87.5	156	202.2	158.7	60	54	475
5.4	87.5	175.5	202.2	163.4	62	54	481
6.8	0.4	136.5	0.9	99.7	38	54	192
6.8	0.4	156	0.9	103.7	39	54	198
6.8	0.4	175.5	0.9	107.2	41	54	203
6.8	8.8	136.5	20.3	108.9	41	54	224
6.8	8.8	156	20.3	113	43	54	230
6.8	8.8	175.5	20.3	116.5	44	54	235
6.8	26.3	136.5	60.8	126.9	48	54	290
6.8	26.3	156	60.8	131.2	50	54	296
6.8	26.3	175.5	60.8	134.8	51	54	301
6.8	87.5	136.5	202.2	178.6	67	54	502
6.8	87.5	156	202.2	184.6	70	54	511
6.8	87.5	175.5	202.2	189.8	72	54	518
9.5	0.4	136.5	0.9	140.9	53	54	249
9.5	0.4	156	0.9	146.6	55	54	257
9.5	0.4	175.5	0.9	151.6	57	54	264

9.5	8.8	136.5	20.3	150.2	57	54	281
9.5	8.8	156	20.3	155.9	59	54	289
9.5	8.8	175.5	20.3	160.9	61	54	296
9.5	26.3	136.5	60.8	168.6	64	54	347
9.5	26.3	156	60.8	174.5	66	54	355
9.5	26.3	175.5	60.8	179.6	68	54	362
9.5	87.5	136.5	202.2	224.6	85	54	566
9.5	87.5	156	202.2	231.9	88	54	576
9.5	87.5	175.5	202.2	238.2	90	54	584
10.8	0.4	136.5	0.9	160.7	61	54	276
10.8	0.4	156	0.9	167.2	63	54	285
10.8	0.4	175.5	0.9	172.9	65	54	293
10.8	8.8	136.5	20.3	170	64	54	309
10.8	8.8	156	20.3	176.6	67	54	318
10.8	8.8	175.5	20.3	182.3	69	54	325
10.8	26.3	136.5	60.8	188.6	71	54	375
10.8	26.3	156	60.8	195.3	74	54	384
10.8	26.3	175.5	60.8	201.2	76	54	392
10.8	87.5	136.5	202.2	246	93	54	595
10.8	87.5	156	202.2	254	96	54	606
10.8	87.5	175.5	202.2	260.9	99	54	616

Costs of parts manufactured by SLS in-house

Bounding Box Height of part (in)	Material Volume of part (in^3)	Bounding Box Cross Section of part (in^2)	Mold Cost ($)	Material Cost ($)	Machine usage Cost ($)	Energy Consumption Cost ($)	Labor Cost ($)	Transportation Cost ($)	Inventory Holding Cost ($)	Unit Supply Chain Cost ($)
1.4	0.4	136.5	14447	1.8	3.2	0.3	68	2.5	3.2	291
1.4	0.4	156	15125	1.8	3.2	0.3	68	2.5	3.2	304
1.4	0.4	175.5	15721	1.8	3.2	0.3	68	2.5	3.2	316
1.4	8.8	136.5	14447	39.7	3.2	0.3	68	55	11	293
1.4	8.8	156	15125	39.7	3.2	0.3	68	55	11	306
1.4	8.8	175.5	15721	39.7	3.2	0.3	68	55	11	318
1.4	26.3	136.5	14447	118.5	3.2	0.3	68	164.4	26.9	297
1.4	26.3	156	15125	118.5	3.2	0.3	68	164.4	26.9	310
1.4	26.3	175.5	15721	118.5	3.2	0.3	68	164.4	26.9	322
1.4	87.5	136.5	14447	394.3	3.2	0.3	68	546.9	82.9	311
1.4	87.5	156	15125	394.3	3.2	0.3	68	546.9	82.9	324
1.4	87.5	175.5	15721	394.3	3.2	0.3	68	546.9	82.9	336
4.1	0.4	136.5	14791	1.8	3.2	0.3	68	2.5	3.2	297
4.1	0.4	156	15428	1.8	3.2	0.3	68	2.5	3.2	310
4.1	0.4	175.5	16290	1.8	3.2	0.3	68	2.5	3.2	327
4.1	8.8	136.5	14791	39.7	3.2	0.3	68	55	11	299
4.1	8.8	156	15428	39.7	3.2	0.3	68	55	11	312
4.1	8.8	175.5	16290	39.7	3.2	0.3	68	55	11	329
4.1	26.3	136.5	14791	118.5	3.2	0.3	68	164.4	26.9	304
4.1	26.3	156	15428	118.5	3.2	0.3	68	164.4	26.9	316
4.1	26.3	175.5	16290	118.5	3.2	0.3	68	164.4	26.9	333
4.1	87.5	136.5	14791	394.3	3.2	0.3	68	546.9	82.9	318
4.1	87.5	156	15428	394.3	3.2	0.3	68	546.9	82.9	331
4.1	87.5	175.5	16290	394.3	3.2	0.3	68	546.9	82.9	348
5.4	0.4	136.5	15168	1.8	3.2	0.3	68	2.5	3.2	305
5.4	0.4	156	16111	1.8	3.2	0.3	68	2.5	3.2	324
5.4	0.4	175.5	16756	1.8	3.2	0.3	68	2.5	3.2	337
5.4	8.8	136.5	15168	39.7	3.2	0.3	68	55	11	307
5.4	8.8	156	16111	39.7	3.2	0.3	68	55	11	326
5.4	8.8	175.5	16756	39.7	3.2	0.3	68	55	11	339
5.4	26.3	136.5	15168	118.5	3.2	0.3	68	164.4	26.9	311
5.4	26.3	156	16111	118.5	3.2	0.3	68	164.4	26.9	330
5.4	26.3	175.5	16756	118.5	3.2	0.3	68	164.4	26.9	343

5.4	87.5	136.5	15168	394.3	3.2	0.3	68	546.9	82.9	325
5.4	87.5	156	16111	394.3	3.2	0.3	68	546.9	82.9	344
5.4	87.5	175.5	16756	394.3	3.2	0.3	68	546.9	82.9	357
6.8	0.4	136.5	15542	1.8	3.2	0.3	68	2.5	3.2	313
6.8	0.4	156	16237	1.8	3.2	0.3	68	2.5	3.2	326
6.8	0.4	175.5	17409	1.8	3.2	0.3	68	2.5	3.2	350
6.8	8.8	136.5	15542	39.7	3.2	0.3	68	55	11	314
6.8	8.8	156	16237	39.7	3.2	0.3	68	55	11	328
6.8	8.8	175.5	17409	39.7	3.2	0.3	68	55	11	352
6.8	26.3	136.5	15542	118.5	3.2	0.3	68	164.4	26.9	319
6.8	26.3	156	16237	118.5	3.2	0.3	68	164.4	26.9	332
6.8	26.3	175.5	17409	118.5	3.2	0.3	68	164.4	26.9	356
6.8	87.5	136.5	15542	394.3	3.2	0.3	68	546.9	82.9	333
6.8	87.5	156	16237	394.3	3.2	0.3	68	546.9	82.9	347
6.8	87.5	175.5	17409	394.3	3.2	0.3	68	546.9	82.9	370
9.5	0.4	136.5	16228	1.8	3.2	0.3	68	2.5	3.2	326
9.5	0.4	156	17550	1.8	3.2	0.3	68	2.5	3.2	353
9.5	0.4	175.5	18211	1.8	3.2	0.3	68	2.5	3.2	366
9.5	8.8	136.5	16228	39.7	3.2	0.3	68	55	11	328
9.5	8.8	156	17550	39.7	3.2	0.3	68	55	11	355
9.5	8.8	175.5	18211	39.7	3.2	0.3	68	55	11	368
9.5	26.3	136.5	16228	118.5	3.2	0.3	68	164.4	26.9	332
9.5	26.3	156	17550	118.5	3.2	0.3	68	164.4	26.9	359
9.5	26.3	175.5	18211	118.5	3.2	0.3	68	164.4	26.9	372
9.5	87.5	136.5	16228	394.3	3.2	0.3	68	546.9	82.9	347
9.5	87.5	156	17550	394.3	3.2	0.3	68	546.9	82.9	373
9.5	87.5	175.5	18211	394.3	3.2	0.3	68	546.9	82.9	386
10.8	0.4	136.5	16355	1.8	3.2	0.3	68	2.5	3.2	329
10.8	0.4	156	17705	1.8	3.2	0.3	68	2.5	3.2	356
10.8	0.4	175.5	18365	1.8	3.2	0.3	68	2.5	3.2	369
10.8	8.8	136.5	16355	39.7	3.2	0.3	68	55	11	331
10.8	8.8	156	17705	39.7	3.2	0.3	68	55	11	358
10.8	8.8	175.5	18365	39.7	3.2	0.3	68	55	11	371
10.8	26.3	136.5	16355	118.5	3.2	0.3	68	164.4	26.9	335
10.8	26.3	156	17705	118.5	3.2	0.3	68	164.4	26.9	362
10.8	26.3	175.5	18365	118.5	3.2	0.3	68	164.4	26.9	375
10.8	87.5	136.5	16355	394.3	3.2	0.3	68	546.9	82.9	349
10.8	87.5	156	17705	394.3	3.2	0.3	68	546.9	82.9	376
10.8	87.5	175.5	18365	394.3	3.2	0.3	68	546.9	82.9	389

Costs of parts manufactured by IM at central location